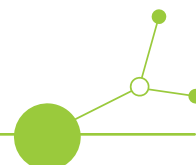


DELIVERABLE 2.2.1

Report on joint circular strategy development to preserve value and reduce waste of public transport infrastructure



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List of abbreviations

Abbreviation	Full Term
AETE	Avoid-Extend-Transform-Enable
BIM	Building Information Modelling
CO2	Carbon Dioxide
CE4CE	Circular Economy for Central Europe
CEAP	Circular Economy Action Plan
EU	European Union
LCA	Lifecycle Assessment
PTO	Public Transport Operator
PTA	Public Transport Authorities
PTI	Public Transport Infrastructure

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Table 1: Analysis of key circular economy regulations and directives for PTI in the EU

Table 2: Non-exhaustive list of circular indicators for PTI



1. Introduction

1.1. Why circularity and the need for the CE4CE strategies?

The transport sector accounts for roughly one-fifth of the total EU emissions. While sectors like energy have reduced emissions since the 1990s, emissions from road transport continue to rise, reaching nearly 700 MtCO₂ as of 2023.¹ The challenge, however, extends beyond tailpipe emissions: the transport sector consumes vast resources, creating significant embedded emissions from activities like steel production for vehicles, gasoline refinement, lithium mining for batteries, and cement manufacturing for infrastructure. For instance, embedded GHG emissions can account for 50-60% of total lifecycle emissions in electric vehicle manufacturing, compared to just 10% for combustion engine cars.²

Emissions are symptomatic of a deeper issue—a linear economy built on a "take-use-throw" model that depletes finite resources and disregards ecological restoration, leading to critical ecosystem exhaustion. Addressing this requires a fundamental shift in how resources are designed, used, and consumed. A circular economy offers a cradle-to-cradle solution, tackling direct ecological impacts of transport activities while addressing the influence and effect in areas like construction, energy, and waste. By rethinking resource use, the circular economy seeks to address the systemic ecological and social impacts of the transport sector and beyond.

The CE4CE project pioneers this shift by transitioning from a linear model to a circular "Avoid-Extend-Transform-Enable" (AETE) approach, positioning public transport as a catalyst for transformation. Its initial phase developed the Circularity Compass³, establishing the AETE framework for understanding public transport activities within a life-cycle perspective, spanning three public transport pillars: Energy, Infrastructure, and Rolling Stock, with Governance as a cross-cutting pillar.

Building on this foundation, CE4CE is advancing **three strategies focused on Energy, Infrastructure, and Rolling Stock**. These strategies leverage the life-cycle approach of the Circularity Compass and adopt a common document structure to uncover the full ecological impacts of each area, exploring in detail their conditions, direct and embedded emissions, and

¹ European Environment Agency. (2024). *Transport and mobility*.

<https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-transport>

² Transport & Environment. (2024). *Cleaning up steel in cars: why and how*.

<https://www.transportenvironment.org/articles/cleaning-up-steel-in-cars-why-and-how>

³ Circular Economy for Public Transport. (n.d.). *Circularity Compass*. <https://circularity4publictransport.eu/circularity-compass/>



sector-specific recommendations to advance a more circular approach. These strategies form the basis for localized action plans, offering concrete, time-bound measures and clearly defined responsibilities to make circularity a reality and drive the transition to net-zero public transport systems.

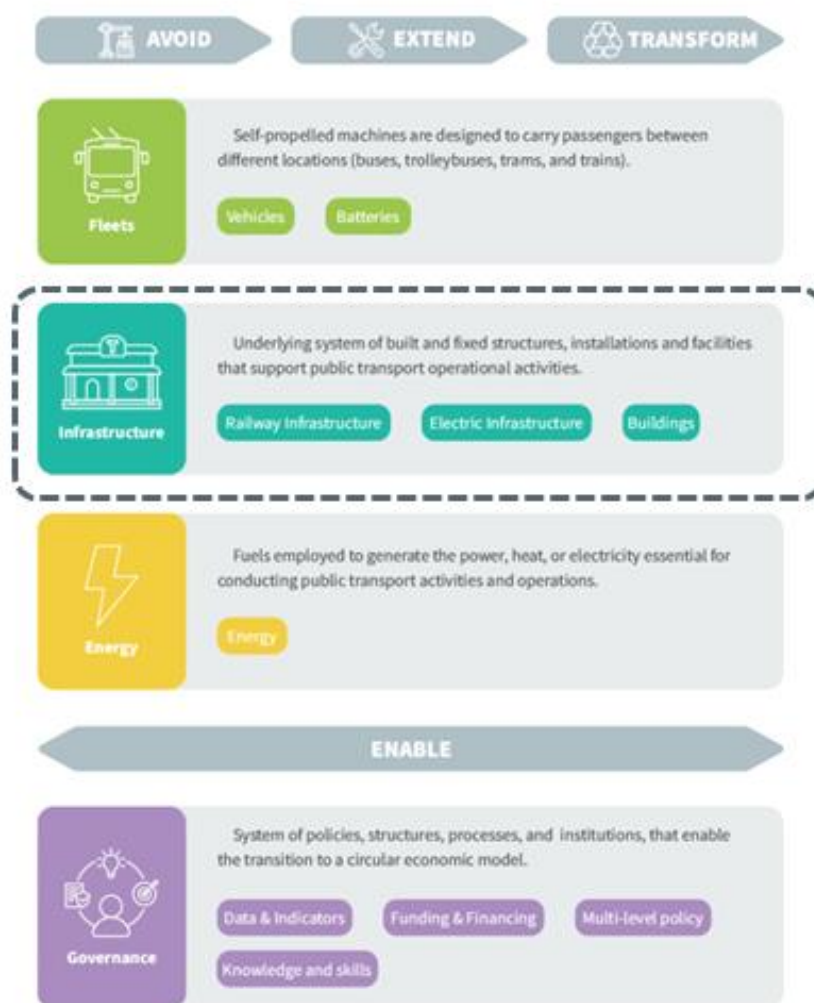


Figure 1. Visual summary of circularity compass life-cycle approach and public transport pillars. The frame highlights the focus of this strategy is on public transport infrastructure elements. Source: CE4CE

1.2. Why a circular economy approach in public transport infrastructure

Public Transport Infrastructure (hereafter, PTI) is fundamental to the functioning of modern society. They enable the movement of people and goods, drive economic activity, and provide essential access to services. However, these assets are often underappreciated in the broader push for sustainable transport solutions, with a focus placed more on vehicles and operations than on the physical infrastructure itself. This oversight can undermine system resilience, reduce long-



term efficiency, and compromise sustainability goals, particularly as the infrastructure ages or is subjected to growing demands.

Nevertheless, and despite their societal value, PTI projects frequently generate substantial environmental externalities. From construction to maintenance and eventual decommissioning, each phase of the public transport infrastructure life cycle can contribute to carbon emissions, resource depletion, and ecological disruption. **Embracing a circular economy approach offers a way forward by rethinking how materials are sourced, used, and repurposed throughout the infrastructure's life.** By integrating circularity into planning and decision-making, stakeholders can enhance environmental performance, reduce waste, and support long-term value creation—ensuring that transport infrastructure not only serves society effectively but also aligns with broader environmental and sustainability objectives.

2. Conceptual and contextual basis

2.1. Approximation to a definition of Public Transport Infrastructure (PTI)

The terms infrastructure and particularly transport infrastructure are part of overlapping activities and sectors, making it challenging to classify and define their scope. Broadly speaking, transport infrastructure belongs to the built environment, which encompasses all physical structures and spaces that support human activities through human intervention and adaptation for specific purposes. The built environment is typically divided into five categories: 1) Buildings (industrial, commercial, institutional), Infrastructure (roads, bridges, airports, power grids, water supply systems, etc.), Public spaces (parks, plazas, sidewalks), Urban systems (city grids and layouts), Environmental features (canals, dams, urban forests). Within this framework, **transport infrastructure** is a subset of the built environment, primarily situated at the intersection of the **infrastructure** category and, to a lesser extent, the **buildings** category.

The classification outlined above aligns somewhat with economic sector categories in the EU. In this framework, transport infrastructure falls under the **buildings and construction sector**, which can be divided into three main categories:

- **Construction of Buildings:** This category includes structures designed for residential, commercial, industrial, or institutional purposes, providing enclosed spaces suitable for human use. In the context of transport, examples include terminals, metro stations, and administrative offices.



- **Civil Engineering:** This encompasses infrastructure projects requiring advanced expertise and specialized techniques, typically involving large-scale public works. Examples include bridges, tunnels, roads, railways, water treatment plants, and sewage systems.
- **Specialized Civil Engineering Works and Construction:** This category refers to highly specialized projects, such as renewable energy installations (e.g., wind farms, hydroelectric dams), structural reinforcements, and other tailored construction techniques designed to meet specific infrastructure needs.

In this broader context, transport infrastructure is a backbone component of transport systems but is categorized outside the road transport sector and the manufacturing subcategory of automotive. Its classification and scope require purpose-built definitions and a nuanced, flexible approach to account for its diverse and interconnected nature.

2.2. Defining public transport Infrastructure for the CE4CE strategy

In the framework of the Circularity compass, the provisional definition of transport infrastructure within the context of public transport systems pillar is: **The underlying system of built and fixed structures, installations, and facilities that support public transport operational activities, forming the foundation of public transport systems.** The circularity compass further breaks down the transport infrastructure pillar in three subpillars:

- **Railway infrastructure** refers to the fixed installations needed to support the operation of rail-based public transport. This includes rail tracks, as well as railway bridges and tunnels.
- **Electric infrastructure** refers to the systems, networks, and facilities required to generate, transmit, distribute, and use electrical energy to power public transport. It includes charging stations, overhead catenary systems, substations, and energy storage systems.
- **Buildings** in public transport are enclosed structures that support operational, administrative, or passenger-related services for the system. Examples include stations, administrative offices, depots for parking, charging, and maintenance, multi-modal parking facilities, and passenger shelters.

It is important to mention that while **road infrastructure is naturally a part of public transport assets, it was not included as an infrastructure element in the CE4CE Circularity Compass for the time being.** This is because PTOs, the main target group of the project's outputs, have little to no influence over its construction or maintenance, which is typically managed by other departments within municipalities. Additionally, road infrastructure serves all transport modes, not just public transport, and does so to a limited extent. Therefore,



understanding, even if just as an approximation, the impact of public transport activities on the lifecycle of road infrastructure would have been very imprecise and complex.

2.3. Introducing a life cycle approach in public transport infrastructure

A first and crucial step in advancing circularity in public transport infrastructure is adopting a life cycle perspective. This is essential for understanding the full range of resource use and ecological impact, as well as for identifying where priorities should be set.

To achieve this, the strategy builds upon existing frameworks. On one hand, it is grounded in the **Circularity Compass Avoid-Extend-Transform-Enable framework**⁴, which, as part of the CE4CE project, has been tested, widely shared, and positively received by a large community of public transport stakeholders. On the other hand, the life-cycle stages align with the **EN 15978 standard**⁵—a non-compulsory, Europe-wide reference providing clarity on life cycle perspectives in buildings, specifically as a framework for conducting life cycle assessments (LCAs). LCAs help measure resource use (such as energy) and associated carbon emissions and have become the standard approach in the construction sector. Since its release, the standard has been adapted to suit specific cases while maintaining its core principles.

For this strategy, a tailored version was developed by combining these two frameworks, aiming to strengthen the circularity aspects and adapt them to the specific conditions and elements of PTI, thereby filling an important gap in guidance for advancing circularity within this sector.

⁴ Circular Economy for Public Transport. (2024). *The Circularity Compass* (Version 2024.12.09). <https://circularity4publictransport.eu/wp-content/uploads/2025/02/The-Circularity-Compass-2024.12.09.pdf>

⁵ British Standards Institution. (2011). *BS EN 15978:2011 Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method*. <https://www.en-standard.eu/bs-en-15978-2011-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/?msclkid=20388604c93b1a91b166ee28445f41f1>

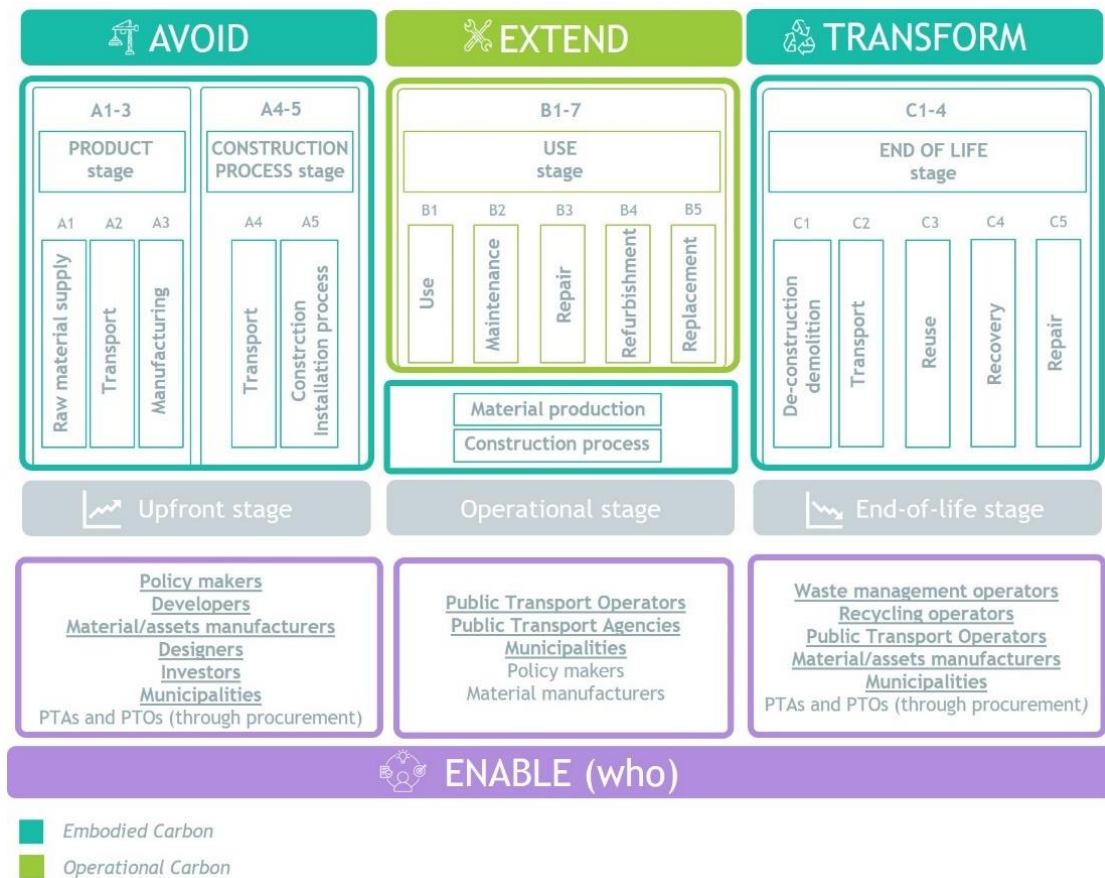


Figure 2. Adapted PTI Life-cycle-based on EN 15978 version

General overview

The PTI life cycle diagram is divided into three main stages: AVOID-upfront (A), EXTEND-operation (B), and TRANSFORM-end of life (C). Each stage is further broken down into specific and essential sub-stages, covering key activities within each phase. Additionally, the enable aspect acts as a cross-cutting element, highlighting the core and secondary actors involved at every stage.

The diagram also depicts two types of energy use and associated emissions: operational and embodied. **Operational energy and associated emissions** (also called direct emissions or Scope 1 emissions) refer to the energy directly generated by the actors or organizations involved in each stage. **Embodied energy and associated emissions** (also called indirect or Scope 2 or 3 emissions) occur outside the organization's direct scope but are still influenced by its activities and have indirect impacts.

As seen in the PTI infrastructure life cycle diagram, Public Transport Operators (PTOs)—and, to a lesser extent, Public Transport Authorities (PTAs) and municipalities—are typically responsible for direct emissions and energy consumption generated during the operational stage. This primarily



refers to energy used for powering systems through catenary or other alternative energy provision infrastructure, as well as for the lighting, heating, and cooling of buildings.

Another important factor, not prominently highlighted in the diagram but crucial in the life cycle assessment (LCA) approach, is **the lifespan of public transport infrastructure (PTI) assets**. While the average lifespan is often estimated at around 50 years, this figure can be misleading because it combines the lifespans of all components. For example, in a building, movable objects or interior elements may last only a few years, whereas structural elements like foundations can last over 100 years or even indefinitely⁶. Similarly, in railway infrastructure, components such as ballast or sleepers have much shorter lifespans than the average, while rails can last for several decades.

AVOID (A-Upfront stage)

As previously mentioned, the upfront stage refers to resource use and associated emissions before PTI becomes operational, and it is divided into two sub-stages:

A1-3 (Product Stage) covers materials procurement for construction, including raw material supply, transport, and manufacturing. This stage emphasizes the importance of decision-making, particularly during planning and design when materials and processes are selected. PTOs and other local transport actors play a role in influencing the choice of materials and energy sources during the procurement process.

A4-5 (Construction Stage) is the phase where the asset is built. During this stage, construction contractors manage resources, including energy consumption, water use, and construction waste on site.

A significant environmental impact comes from materials production and associated emissions, known as embodied carbon in the PTI life cycle. The large impact stems from the reliance on high carbon-intensive materials like cement and steel, specifically from energy-intensive mining processes, the energy needed for manufacturing (often sourced from non-renewable fuels), and high transportation costs for importing materials, often from overseas. The associated embodied

⁶ World Green Building Council. (2019). *Bringing embodied carbon upfront: Coordinated action for the building and construction sector to tackle embodied carbon*. https://worldgbc.s3.eu-west-2.amazonaws.com/wp-content/uploads/2022/09/22123951/WorldGBC_Bringing_Embodied_Carbon_Upfront.pdf



carbon in buildings is substantial, accounting for roughly 11% of global GHG emission⁷, with the construction sector contributing significantly, as 50% of materials are used in this sector⁸.

While specific information on PTI is limited, some examples provide insight. For instance, a study on Swedish railways shows that high carbon materials like cement, and steel account for more than 80% of materials used⁹. Additionally, as shown in the image, material production (A1-3) contributes three-quarters of emissions compared to the construction phase itself¹⁰.

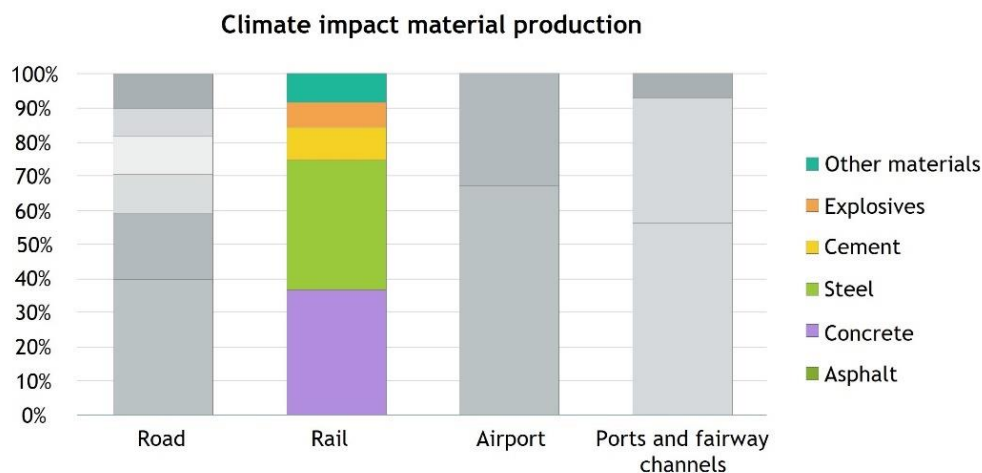


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Source: Adapted based on Liljenström, C., Toller, S., Åkerman, J., & Björklund, A. (2019).

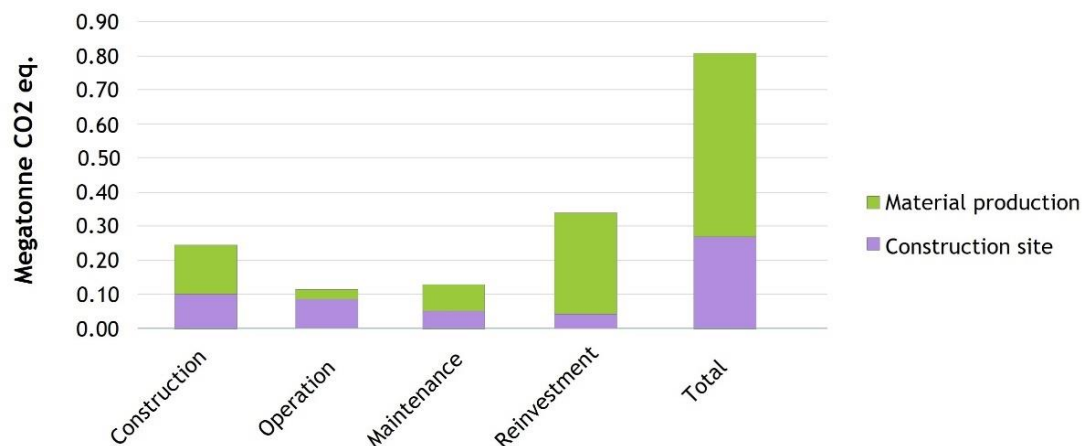


Figure 4. Impact of material production and associated embodied carbon along the lifecycle of Swedish railway infrastructure
Source: Adapted based on Liljenström, C., Toller, S., Åkerman, J., & Björklund, A. (2019).

⁷ World Green Building Council. (n.d.). *Bringing embodied carbon upfront*. <https://worldgbc.org/climate-action/embodied-carbon/#:~:text=Embodied%20carbon%20emissions%20have%20historically,carbon%20in%20their%20decarbonisation%20strategies>.

⁸ European Commission. (n.d.). *Buildings and construction*. https://single-market-economy.ec.europa.eu/industry/sustainability/buildings-and-construction_en

⁹ Liljenström, C., Toller, S., Åkerman, J., & Björklund, A. (2019). *Annual climate impact and primary energy use of Swedish transport infrastructure*. *European Journal of Transport and Infrastructure Research*. <https://doi.org/10.18757/ejtir.2019.19.2.4378>



In addition, available information on building cases highlights how the ecological footprint of the upfront stage has become increasingly critical. While recent advancements in energy use, technology, and techniques have significantly reduced operational energy consumption, embodied energy and emissions are rising. Recent estimates suggest that while embodied carbon once accounted for around 20% of total building emissions, it will represent about half by 2050¹¹. This shift is mainly due to material production and selection. A study comparing construction materials found that embodied carbon emissions from concrete and steel are roughly 40% and 80% higher, respectively, than those from timber components¹².

EXTEND (B- Operational stage)

The operational stage refers to the energy, materials, and processes deployed throughout the asset's lifespan to keep it running. This includes daily operations, regular maintenance, and major upgrades.

The operational stage still accounts for the largest share of resource use and emissions, as the lifespan of PTI is prolonged, often averaging 50 years. Information for non-residential buildings shows that energy consumption can vary widely, with typical buildings using about 80% of energy compared to only 30% for high-end energy-efficient counterparts. For railways, information is scarce, but a study comparing various European systems indicates that track operation and maintenance contribute between 6% and 17% of CO₂-equivalent emissions. Notably, the overwhelming majority of emissions—over 70%—come from rolling-stock-related activities¹³.

Studies indicate that energy use and associated emissions have significantly decreased in recent years. In buildings specifically, this is due to using more efficient materials, techniques, and technologies, which reduce electricity consumption for lighting, HVAC systems, and heating. A similar trend, driven by technical and technological advancements, can probably be assumed for railway and electric infrastructure¹⁴.

Nevertheless, the situation is less encouraging when considering embodied carbon from material production and construction activities at this stage. This is largely due to the aging of many assets that require repair or renewal in Europe. For instance, in Germany, it is estimated that by 2025,

¹¹ Julianus, S. (2019). *Embodied carbon: Why does it matter?* Shepley Bulfinch. <https://shepleybulfinch.com/embodied-carbon-why-does-it-matter/>

¹² Schenk, D., & Amiri, A. (2022). Life cycle energy analysis of residential wooden buildings versus concrete and steel buildings: A review. *Frontiers in Built Environment*, 8, Article 975071. <https://doi.org/10.3389/fbuil.2022.975071>

¹³ Jones, H., Moura, F., & Domingos, T. (2017). Life cycle assessment of high-speed rail: A case study in Portugal. *The International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-016-1177-7>

¹⁴ Sharma, A., Saxena, A., Sethi, M., Shree, V., & Varun. (2011). Life cycle assessment of buildings: A review. *Renewable and Sustainable Energy Reviews*. <https://doi.org/10.1016/j.rser.2010.09.008>



17% of the total railway track will need renewal, while around 35% will require repair¹⁵. In buildings, the situation is similar, with currently about 35% of buildings in Europe being 50 years old or older, and 97% of the building stock is not efficient enough to comply with future carbon reduction targets¹⁶.

To give an idea of the magnitude of the impact on emissions, a study on Swedish railways highlights that embodied carbon from material production is, in fact, significantly bigger at the reinvestment stage, that is when major upgrades are needed, than at the initial construction stage¹⁷.

TRANSFORM (C-End-of-life stage)

The end-of-life phase includes all activities when assets can no longer be used or their lifespan extended. At this stage, assets must be dismantled, dismounted, or demolished.

Construction has a significant environmental impact. Globally, about 50% of all extracted materials feed the construction sector, including large volumes for transport and public transport infrastructure. This sector generates roughly 30% of all construction and demolition (C&D) waste¹⁸ and contributes notably to greenhouse gas emissions, with landfilling accounting for an estimated 5% of global emissions¹⁹.

In the EU, recycling rates for C&D waste vary but have risen steadily, exceeding 70%. However, most recycled materials are downcycled into lower grade uses like road sub-bases instead of being reused for their original high-performance structural roles²⁰. This practice fails to reduce demand for virgin raw materials such as steel, gravel, and cement, widely used in transport infrastructure. Consequently, the sector remains dependent on new materials, increasing embodied carbon and greenhouse gas emissions.

¹⁵ Deutsche Bahn AG. (2025, April 15). *Trendwende eingeleitet: DB InfraGO legt neuen Zustandsbericht vor*. https://www.deutschebahn.com/de/presse/pressestart_zentrales_uebersicht/Trendwende-eingeleitet-Zustand-der-Infrastruktur-2024-verbessert-13362620

¹⁶ World Green Building Council. (2019). *Bringing embodied carbon upfront: Coordinated action for the building and construction sector to tackle embodied carbon*. https://worldgbc.s3.eu-west-2.amazonaws.com/wp-content/uploads/2022/09/22123951/WorldGBC_Bringing_Embodied_Carbon_Upfront.pdf

¹⁷ Liljenström, C., Toller, S., Åkerman, J., & Björklund, A. (2019). Annual climate impact and primary energy use of Swedish transport infrastructure. *European Journal of Transport and Infrastructure Research*. <https://doi.org/10.18757/ejtir.2019.19.2.4378>

¹⁸ European Commission. (n.d.). *Buildings and construction*. https://single-market-economy.ec.europa.eu/industry/sustainability/buildings-and-construction_en

¹⁹ Zhang, C., Xu, T., Feng, H., & Chen, S. (2019). Greenhouse gas emissions from landfills: A review and bibliometric analysis. *Sustainability*, 11(8), 2282. <https://doi.org/10.3390/su11082282>

²⁰ European Environment Agency. (2020). *Construction and demolition waste: Challenges and opportunities in a circular economy*. <https://www.eea.europa.eu/publications/construction-and-demolition-waste-challenges/construction-and-demolition-waste-challenges>



To accelerate circularity in construction, key challenges must be addressed. Demolition processes need better organization, new technologies, and selective dismantling to improve sorting and material recovery. Economic incentives and cost-effective recycling solutions should be promoted to make recycled materials competitive with new ones. Establishing standardized certifications and quality assurance will build trust in reused and recycled materials for structural use. Additionally, raising awareness and expanding pilot projects will highlight the benefits of circular construction, encouraging market acceptance and innovation.

Critically, reuse should be prioritized over recycling. Recycling often requires energy and resources comparable to new material production. The largest untapped potential at end-of-life lies in directly reusing materials and components. A Finnish housing project using prefabricated concrete panels showed significant environmental and economic gains: the carbon footprint of reused panels was almost negligible compared to recycled or new concrete, with construction costs reduced by 20-30%.²¹

This potential will increase if future buildings are designed for easy disassembly and modular reuse, allowing components to be efficiently repurposed.

Ultimately, recycling or reuse efforts must be paired with stricter limits on new material procurement. Only by reducing new material consumption and maximizing existing resource use can the sector curb its growing demand for virgin materials, regardless of recyclability.

2.4. Regulatory framework

2.4.1. Introduction to the Circular Economy regulatory landscape in the EU

The regulatory landscape governing circular economy in public transport is characterised by a multi-tiered legal and policy framework, blending **binding legislations**, **strategic action plans**, and **supporting guidelines**. The enforceability of these instruments varies depending on their legal nature—whether they are **regulations**, **directives**, **decisions**, or **non-binding initiatives**—and on how they are implemented and monitored across Member States. This multilayered regulatory approach ensures that circular economy principles are embedded in EU legislation while allowing flexibility for Member States in implementation. At the core of this regulatory landscape is the European Green Deal²². It is EU's ambitious and overarching policy framework that aims to make

²¹ Hopkinson, P., Chen, H.-M., Zhou, K., Wang, Y., & Lam, D. (2018). Recovery and re-use of structural products from end-of-life buildings. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, 171(3), 180-190. <https://doi.org/10.1680/jensu.18.00007>

²² European Commission. (2020). *The European Green Deal*. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en



Europe a climate-neutral continent by 2050 and to decouple growth from resource use and environmental degradation. It encompasses a broad spectrum of interconnected initiatives that address issues ranging from climate change to social fairness.

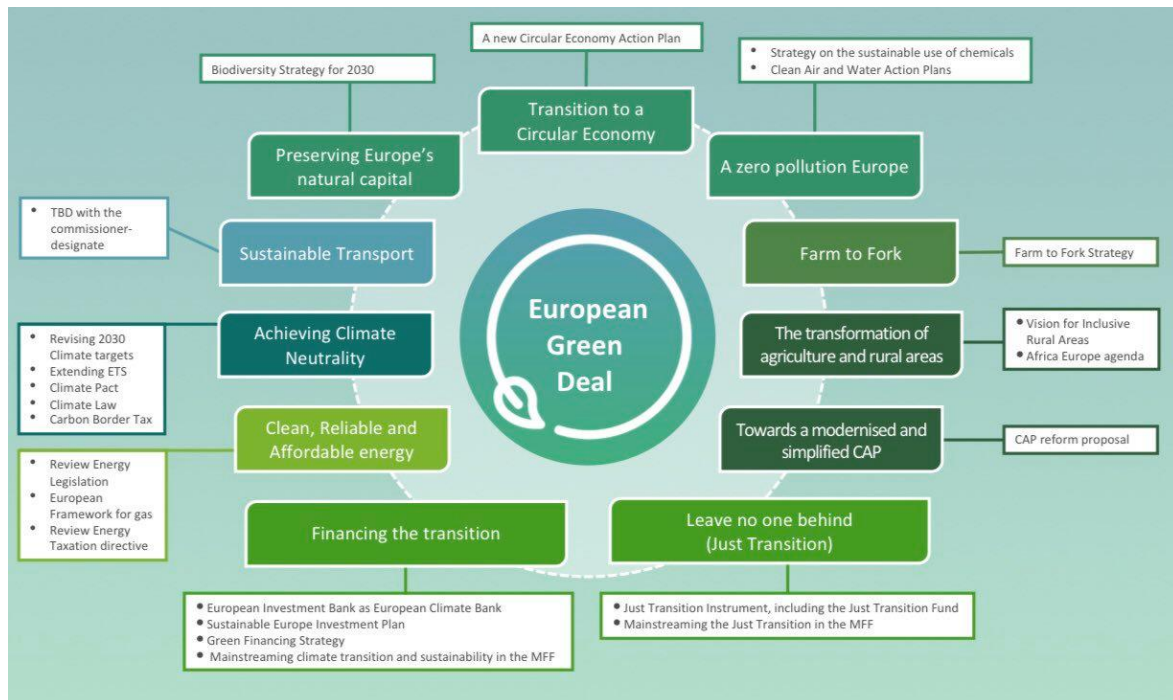


Figure 5. Framework of the European Green Deal. Source: The European Green Deal - European Commission

Supporting the Green Deal is the **Circular Economy Action Plan (CEAP)**, which provides a framework of measures to implement circularity in the European economy. Updated in 2020, the CEAP prioritizes sectors with significant environmental impact, such as transportation, and promotes design and production practices that extend product lifespans and facilitate circular use.

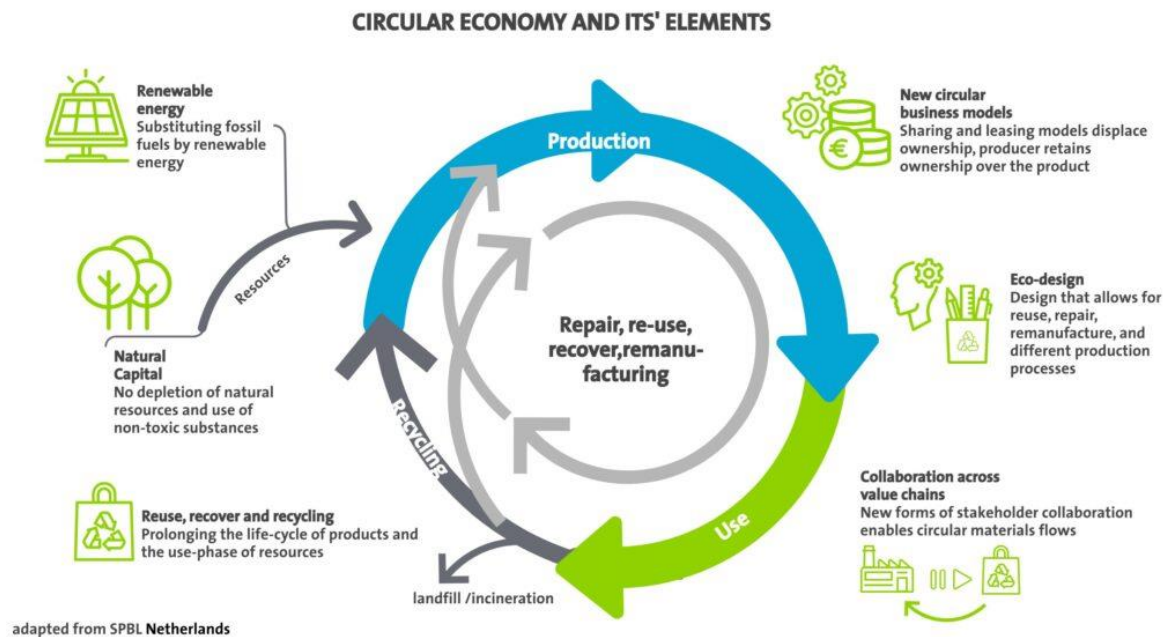


Figure 6. Circular Economy Action Plan and associated domains of influence Source: The Circular Economy Action Plan and its external Dimension.

The cornerstone of the action plan is to design and promote sustainable products that are durable, repairable, reusable, recyclable, and energy- and resource-efficient. The relevant product value chains which the action plan focusses on are: ‘Batteries and vehicles’ and ‘Construction and Buildings’ - both of which have direct implications on the public transport stakeholders. Public procurement, representing about 14% of the EU GDP ([Special report 28/2023: Public procurement in the EU](#)), will be leveraged to drive demand for sustainable products through mandatory green public procurement criteria and reporting. This would have a significant impact on the public transport stakeholders such as city authorities and PTAs who are heavily involved in procurement, especially of vehicles and associated components.

The above strategies are not legally binding. Rather, they serve as high-level frameworks that guide and shape legislative development. They also influence **funding allocations** (e.g., Horizon Europe, Cohesion Policy Funds, Just Transition Mechanism), by acting blueprints that steer EU financial resources toward sustainability and circularity. Hence, these strategic instruments translate high-level policy goals into concrete investments. For public transport stakeholders, this means that aligning projects with circular economy and climate objectives is increasingly essential to access EU funding, fostering innovation and infrastructure modernization that support Europe's green and just transition ambitions. The core enforceable elements of the EU's circular economy strategy are contained in **regulations** and **directives**. A few good examples are the **Waste Framework Directive (2008/98/EC)** which sets binding waste management targets and principles,



the **Eco-design Directive (2009/125/EC)** that enforce design standards on products and raw materials, and the **Energy Performance of Building Directive** that enforce building construction compliances. They set binding targets and outcomes but leave Member States discretion over the means of implementation. All these policy instruments aggregate together in implementing circularity within different aspects and at several scales in the domain of public transport infrastructure.

Finally, we have the non-binding soft laws such as guidelines and standards. For e.g., the Green Public Procurement (GPP)²³ criteria or the Digital Products Passport (DPP)²⁴ - While these tools are not legally enforceable, they enable compliance with mandatory legislation and help stakeholders—particularly public authorities and industries—align with EU environmental expectations.

2.4.2. Analysis of key circular economy regulations and directives in the EU

The following table gives a list of the major circular economy related policies and regulatory frameworks that are relevant from the public transport infrastructure perspective in Europe. It consists of a brief about the focus of the policy, its description and the main targets within it. Most importantly, it lists out the different public transport stakeholders who shall be affected by these policies/regulations and an analysis of how they would be affected.

²³ European Commission. (n.d.). *Green public procurement*. https://green-forum.ec.europa.eu/green-public-procurement_en

²⁴ European Commission. (2022, March 30). *Proposal for a regulation of the European Parliament and of the Council establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC (COM(2022) 142 final)*. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0142>

Table 1: Analysis of key circular economy regulations and directives in the EU

Policy name (date first, include hyperlink)	Focus	Policy description	Policy targets	PT stakeholders affected/involved	Impact assessment on PT stakeholders
EU circular Economy Action Plan (2020) ²⁵	Accelerate the transition to a circular economy in Europe	Promotes sustainable product design, circular processes, and waste reduction. It targets stakeholders from six key value chains and sectors those are: Electronics and ICT, Batteries and Vehicles, Packaging, Plastics, Textiles, and construction and buildings	Double the circular material use rate in the next decade Reduce waste by 50% in major sectors such as construction and demolition by 2030 Achieve a recycling rate of 70% for municipal waste by 2030	PTOs, PTAs, public authorities and waste management sectors, battery and vehicle manufacturers	Promotion of Circular Infrastructure Design - the plan encourages the use of secondary raw materials and recycled content in infrastructure projects such as railway stations, metro lines, tram depots, bus terminals, and maintenance workshops. Encouraging digital tools (e.g., BIM—Building Information Modelling) to optimize resource use during infrastructure design, construction, and operation - greater compliance and cost factor on PTAs. Need to invest in training and capacity building to integrate circular economy principles in infrastructure planning, project management, and maintenance operations.

²⁵ European Commission. (n.d.). *Circular economy action plan*. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en
European Commission. (2020, March 11). *A new Circular Economy Action Plan: For a cleaner and more competitive Europe* (COM(2020) 98 final). https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF

Energy Performance of Building Directive²⁶	To achieve a fully decarbonised building stock by 2050	Improving energy efficiency, reducing greenhouse gas emissions, and promoting sustainable mobility infrastructure, including electric vehicle (EV) charging and bicycle parking facilities in buildings, as part of the EU's circular economy and climate neutrality goals.	Member States required to establish long-term renovation strategies targeting decarbonization of the building stock by 2050.	PTAs, PTOs, Building/construction sub-contractors.	Minimum Energy Performance Standards (MEPS) for Buildings - for both existing and under-renovation buildings. Increased investment requirements expected. Sustainable Mobility Infrastructure Installation - Installation of EV recharging points, pre-cabling, and bicycle parking in buildings with parking spaces. Burden of regulation and investment in short run, with potential for long-term sustainability and cost savings. Energy Performance Certification (EPC) and Reporting - Buildings offered for sale or rent must have EPCs disclosing energy consumption, renewable energy use, and improvement recommendations. National Building Renovation Plans (NRPs) - PTAs will interact with NRPs when planning upgrades or new construction, potentially accessing funding and support. Phase-Out of Fossil Fuel Heating/Cooling Systems - This may mean upfront retrofit costs but contributes to
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²⁶ European Commission. (n.d.). *Energy Performance of Buildings Directive*. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

					sustainability and compliance with EU energy policies. Smart energy management and digitalisation of building operations.
Waste Framework Directive²⁷	Sustainable waste disposal	The policy sets a regulatory framework for the sustainable and non-harmful disposal of waste materials. It explains when waste ceases to be waste and becomes a secondary raw material, and how to distinguish between waste and by-products. The Directive also introduces the "polluter pays principle" and the "extended producer responsibility". It also introduces the 5-step "waste hierarchy", that establishes an order of preference for managing and disposing of waste.	Pushing for increased ambition in member states to meet or exceed the EU target of 70% recycling of non-hazardous Construction & Demolition (C&D) waste by 2020.	PTAs, PTOs, Local Governing bodies, Third-party contractors/sub-contractors.	It is a broad framework that includes a wide category of waste materials. The construction demolition waste category could be considered relevant to the public transport sector. Legal Definition of Construction and Demolition Waste - Public transport projects must identify waste under this category to comply with separate collection and recycling mandates. Separate Collection - procedures to separate C&D waste on-site. This can enable higher recycling rates and reduces contamination of recyclable materials but requires contractors to adapt logistics and workforce training. Waste Hierarchy - PTAs and PTOs must integrate this to operational cycle of buildings - i.e. prevention of waste generation during construction, maximizing reuse of building materials, and prioritizing recycling.

²⁷ European Commission. (2023). *Waste Framework Directive*. https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en



				CE4CE	List of Recovery Operations - this must be complied with. For e.g. recycling of concrete and bricks or soil reuse in backfilling.
Ecodesign for Sustainable Products Regulation (ESPR)²⁸	Sustainable and circular product design standards	To improve the sustainability of products placed on the EU market by improving their circularity, energy performance, recyclability and durability.	Varying targets to increase recycling and repairability in various sectors associated with public transport infrastructure such as iron & steel, aluminium etc.	PTOs, PTAs, Vehicle and component manufacturers, Vehicle repairs and maintenance garages.	The stakeholders need to undertake the following steps: Manufacturers - Design vehicles to meet ESPR guidelines - i.e. durable, modular, and repair-friendly. PTOs - Direct impacts in fleet management and procurement processes - i.e., prioritize EPSR compliant vehicles and equipment. Might incur higher upfront costs, but could achieve long-term savings through extended lifespan, re-use and recycling opportunities. PTAs - Revise tendering criteria to incorporate ESPR compliance, aligning purchasing decisions with sustainability and circularity goals Digital Products Passport - provide comprehensive information about each product's origin, materials, environmental impact, and disposal recommendations. Provide transparency

²⁸ European Commission. (2024). *Ecodesign for sustainable products regulation*. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en



					across supply-chain. PTAs and PTOs need to utilise DPP info in procurement, life-cycle management and end-of-life stages of vehicles and buildings.
Construction Products Regulation (CPR)²⁹	Harmonization of standards and performance requirements for construction products and enable their free movement and uniform marketing within EU.	This regulation lays down harmonised rules for the marketing of construction products in the EU. The Regulation provides a common technical language to assess the performance of construction products. It ensures that reliable information is available to professionals, public authorities, and consumers, so they can compare the performance of products from different manufacturers in different countries.	No specific target. It is rather a product standardization document.	PTAs, PTOs, Infrastructure sub-contractors.	PTAs, procurement bodies and construction/infrastructure subcontractors could better define performance requirements using the harmonised European standard or European Assessment Document. CE certification marking on construction products would entail additional technical obligations on the procurement side for PTAs.

²⁹ European Commission. (n.d.). *Construction Products Regulation (CPR)*. https://single-market-economy.ec.europa.eu/sectors/construction/construction-products-regulation-cpr_en



Clean Industrial Deal³⁰	To turn decarbonisation into a driver of growth for European industries	To enhance the EU's manufacturing capacity for net-zero technologies, support a resilient green supply chain. It simplifies permitting processes, sets clear targets for strategic technologies (e.g., batteries, renewable energy, carbon capture), and establishes "Net-Zero Industry Academies" to reskill the workforce. The Act also emphasizes circularity and resource efficiency, mandating the reuse, repair, and recycling of industrial components and materials.	Increase circular material use to 24% by 2030, from 11.8% today.	PTOs, PTAs, Municipal bodies, vehicle manufacturers.	Increased funding - €100 billion in public and private investment through mechanisms like the Industrial Decarbonisation Bank, InvestEU, and the Innovation Fund. Public procurement - Inclusion of non-price criteria focusing on sustainability, circular economy principles, and EU content requirements. Additional procurement regulations for PTAs, but beneficial in longer run. Voluntary Low-Carbon Product Labelling - this will help PTAs identify and preferentially use materials with lower carbon footprints. Trans-Regional Circularity Hubs and Recycling Initiatives - to pool and process recyclable materials and components. Can improve the availability and quality of secondary raw materials for vehicle parts and infrastructure components.
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³⁰ European Commission. (2025, February 26). *Clean Industrial Deal*. https://commission.europa.eu/topics/eu-competitiveness/clean-industrial-deal_en



Green Public Procurement³¹	Public procurement for better environment	A voluntary policy instrument whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle.	Varying targets on procurement in different sectors associated with public transport.	PTOs, PTAs, Vehicle and component manufacturers	PTAs - procure vehicles that comply with latest emission norms such as Euro VI or alternative fuel (electric, hybrid, biofuels etc.) - 100% compliance by 2025 PTOs - Monitoring of emissions + documentation and verification of the same - E.g. emission certificates, Independent 3rd party verification of retrofitted emission systems on vehicles. Mandatory technology requirements - Traffic information and route optimization systems must be embedded in vehicles, TPMS (Tyre Pressure Monitoring Systems) and low rolling resistance tyres must be included in all vehicles.
Corporate Sustainability Reporting Directive (CSRD)³²	Improve corporate transparency in sustainability	Requires large and publicly listed companies in the EU to disclose detailed, standardized information about their sustainability practices, including environmental impacts, social responsibilities, and	Applies to all large companies (over 250 employees, €40 million turnover, or €20 million balance sheet total) and all companies listed on EU regulated markets (except micro-enterprises)	Public Transport Operators (PTOs), Subcontract suppliers, City/Municipal authorities	PTOs will be mandated to do the following: Double materiality assessment: Assess and disclose sustainability-related information from environmental + social perspective and financial perspective. Adherence to European Sustainability Reporting Standards (ESRS) regulation -

³¹ European Commission. (n.d.). *Green public procurement*. https://green-forum.ec.europa.eu/green-public-procurement_en

³² European Commission. (n.d.). *Corporate sustainability reporting*. https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en



		governance structures (i.e. ESG practices)			report on resource inflows (e.g., fuel, materials) and outflows (e.g., emissions, waste) Supply chain transparency - report on environmental impact across supply chain. Stakeholder Engagement - establish regular communication channels, such as surveys or community meetings, to gather feedback on sustainability initiatives. Digital Reporting Formats - Reports must be prepared in a digital, machine-readable format, adhering to the European Single Electronic Format (ESEF).
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In summary, the diverse range of circular economy policies analysed highlights a comprehensive approach within Europe to foster circularity and sustainability across various sectors. Each policy targets specific areas, from infrastructure design and construction to end of life or disposal. Public transport stakeholders stand to experience significant impacts, both in operational practices and environmental outcomes. Collectively, these policies not only promote resource efficiency and waste reduction but also pave the way for a more resilient public transport system, aligning with circularity goals. These initiatives underscores the importance of continued collaboration among policymakers, industry, and public transport entities to maximize the benefits for Europe's transition to a circular economy.

3. Status Quo analysis

This section provides an overview of the implementation of circularity approaches, principles, and solutions in public transport systems in Europe, along with the associated challenges and opportunities. For the development of this section, data collection was initially carried out using the three infrastructure surveys previously developed for **the Circularity Compass self-assessment tool**³³. A targeted outreach process was conducted, reaching out to PTOs via targeted emails, project and partner newsletters, and LinkedIn posts. Overall, responses were collected and validated from **12 PTOs across 14 European cities**. These responses covered the following categories:

- **Railway infrastructure:** 12 responses
- **Catenary/electric infrastructure:** 11 responses
- **Buildings:** 9 responses

In addition to this process, a series of follow-up interviews were conducted to gain further insights into the survey results and better understand the underlying reasons. In total, three interviews were conducted.

As the survey structure is organized following the AETE framework adopted in the Circularity Compass, the results are presented in line with that framework.

Several limitations should be noted in the data collection process. Reaching Public Transport Operators (PTOs) was challenging, with many accessing the survey but leaving it incomplete, likely due to its length. Interviews were also difficult to conduct, as key respondents were often unavailable. Language barriers further hindered participation, as many potential respondents were not confident in English, making them reluctant to complete the survey or engage in interviews. Additionally, the geographical scope was limited, with most responses coming from Central Europe—an expected outcome given the project's base in that region. As such, the findings may not fully represent the broader European context, and more extensive, geographically diverse data collection would be necessary for more generalizable conclusions.

The survey and interviews followed the circularity compass framework, with questions framed to align with the Avoid- Extend - Transform - Enable format. The Avoid phase focusses on approaches and strategies to prevent unnecessary extraction of primary raw materials and resources. The 'Extend' phase focusses on the ways and means to extend the life and usage of the components

³³ trolley:motion (2024). The Circularity compass self-assessment tool. <https://circularity4publictransport.eu/self-assessment-selection/>



as long as possible. The ‘Transform’ phase investigated the end-of-life stage strategies such as recycling and repurposing that gives a new life to the input resources used. Finally, the ‘Enable’ phase focussed on the policies, capacities and institutional framework that enable the implementation of circularity concepts within the organisation.

3.1. General information

At the beginning of the survey, participants were asked to provide information on specific functions related to infrastructure as well as their motivations to advance the circular economy in this area.

Regarding the specific ownership and function of PTI, it can be concluded that PTOs do not have full ownership or agency in this realm. PTOs typically do not have full authority or responsibility over railway infrastructure, as their role is more focused on operation and maintenance. Municipalities generally own the infrastructure and make major decisions, including having the final say in selecting third parties for design and construction through tendering processes. This situation is similar for buildings, such as stations and shelters, which are usually owned by the municipality or a real estate entity. Depots or offices may vary in ownership, with some being owned by the PTOs.

Regarding motivators for adoption of CE in PTI, survey responses outlined that the two main motivations for PTOs to pursue circularity were the need to be a sustainable/low-emission footprint company and to adopt modern technical solutions that make them a future-proof undertaking. Getting ahead of policy regulations was the least ranked motivation among the respondents.

3.2. Avoid stage

Advancements in implementing circularity in building construction and retrofitting

The survey responses for the buildings survey suggest that **PTOs have greater authority in implementing circularity measures in both new and old buildings** over the past five years, with most respondents indicating a moderate to full extent of implementation for several given measures, as seen in Figure 7. From the interviews, it seems that the area where it seems there has been more **progress in incorporating circularity at the stage is in the design and construction of new buildings**. The conditions appear to be in place to support more sustainable design, including the availability of know-how, techniques, materials, and the enforcement of local and national regulations. For example, one PTO highlighted a recent building project that



incorporated low-carbon materials like timber, as well as energy efficiency technology, like centralized temperature management systems, passive insulation, and even the use of otherwise wasted energy in certain cases (e.g., using excess building heating to warm paint for rolling stock painting).

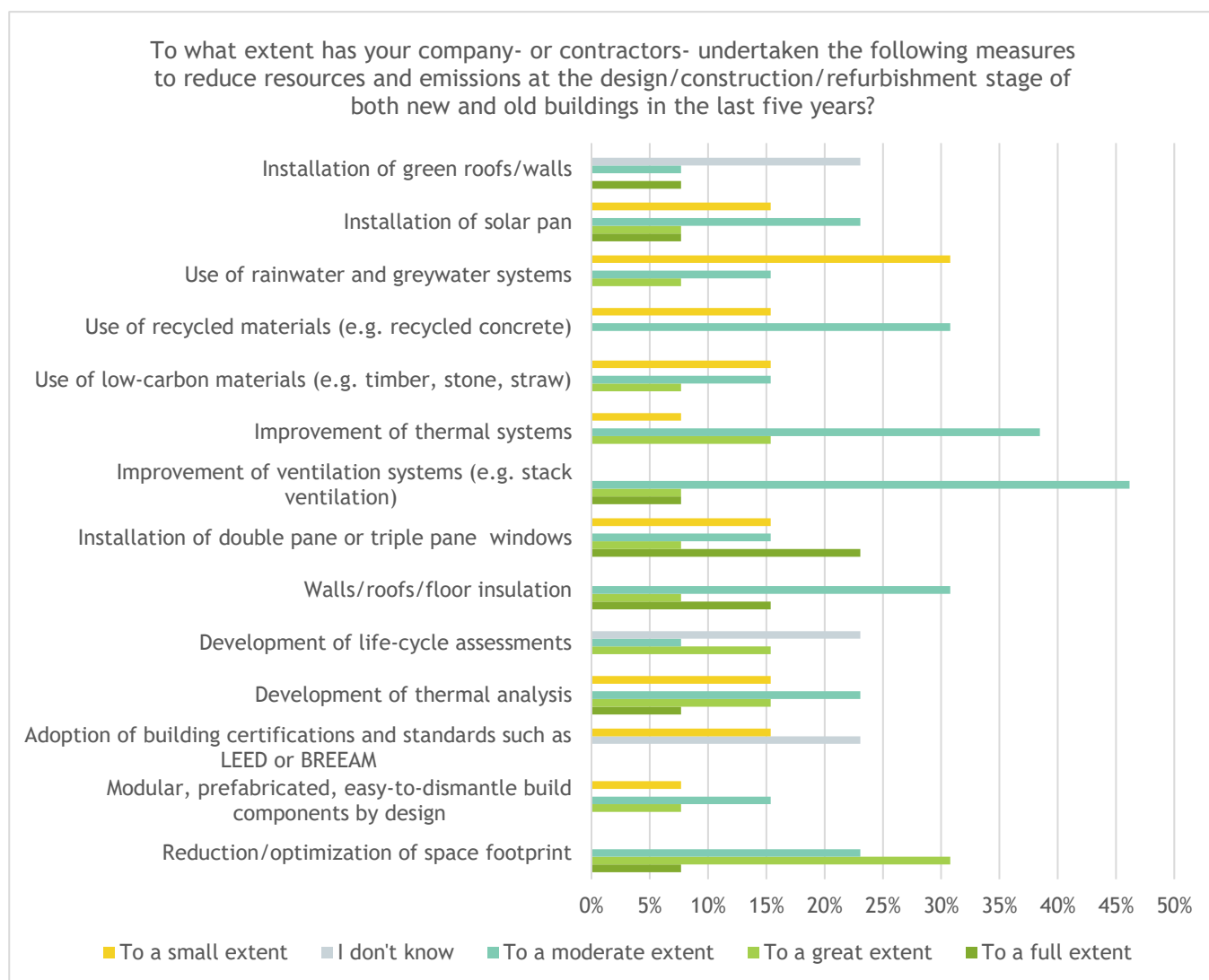


Figure 7. Survey response on implementation of circularity concepts in PTO buildings

Reducing energy consumption in infrastructure, has also become high priority in public transport infrastructure as a whole, indirectly advancing circularity. Due to rising energy prices in recent years, PTOs have made significant progress in being more mindful and stringent with energy use, consistently working to reduce demand. Going off-grid by installing solar panels has also become a strategy to reduce reliance on fossil fuels and ensure the provision of clean, local energy for certain activities.



Estimation of materials and resource usage in the sector

There is a general lack of awareness regarding the estimation of materials used and chosen in infrastructure design and construction. Estimating resource usage is not seen as a high priority by respondents. However, one respondent highlighted their active interest in conducting material flow analysis for future projects, with the goal of minimizing resource use from the outset or being better informed to make decisions about handling resources later on.

Nonetheless, material estimation is a more common practice—especially in railway infrastructure—than it may seem at first glance. PTOs reported relatively consistent and even accurate estimates for certain materials, such as steel, ballast, gravel, and concrete, when used for construction and retrofitting activities, particularly on smaller sections of the railway that are handled in-house. This contrasts with the rail infrastructure survey results where there were as many number of respondents who reported being unaware of the quantity estimations, as there were the ones who were aware of the same. This might be due to the fact that when the construction of new infrastructure or retrofitting is outsourced to contractors, material estimations become more difficult, as contractors often do not provide accurate information—or any information at all—on the quantities used. Similarly, survey respondents consistently reported a **lack of awareness of the quantity estimations of important materials used in building construction**. That said, the PTOs in electric infrastructure domain reported to possess a good estimate of all major materials used such as copper, steel and aluminium, as shown in Figure 8.

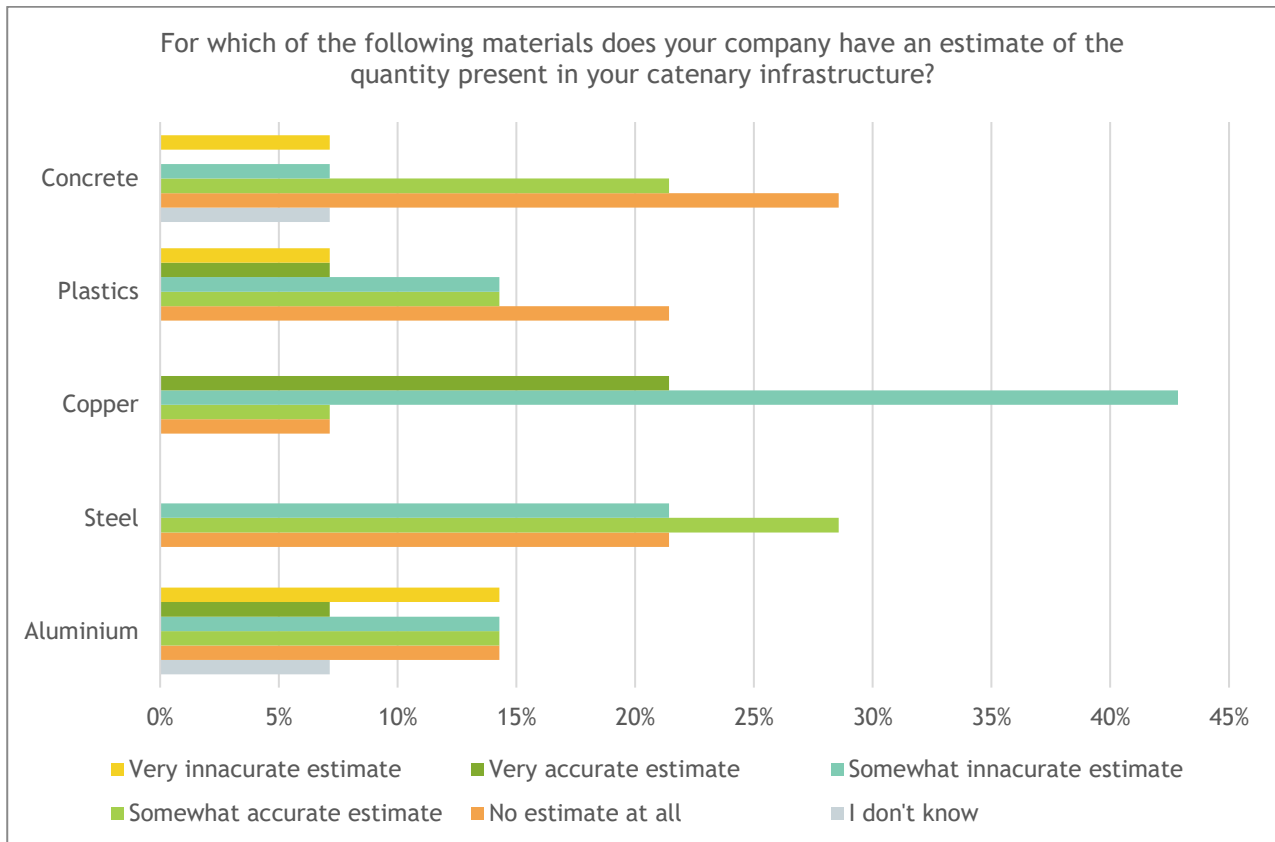


Figure 8. Quantity estimation of different materials used by PTOs in Electric infrastructure domain

3.3. Extend stage

In contrast to the previous stage, insights gathered from the interviews indicate that PTOs possess a wealth of information and agency at this stage. This is logical, as it falls within their scope of work and is essential for integrating with day-to-day operations.

Overall condition of existing infrastructure

Most respondents acknowledged that **while the infrastructure—is not in optimal condition, significant improvements have been made and will continue.** Particularly in Central Europe and Eastern Europe, much of the original infrastructure dates back to the Soviet era, which has led to ongoing maintenance and the challenge of addressing the neglect of previous years.

In the railway sector, for example, it is common to find a mix of well-maintained and regular-poorly-maintained infrastructure. More than 30% of the survey respondents in this domain reported their rail network to be in 'Good' condition, while more than half of them reported it to be in 'Regular' condition. One tangible consequence of this is the inability to achieve higher speeds and improved travel times in certain segments, which potentially affects ridership.



In the rail infrastructure domain, regular and standardized check-up was reported as the key method to extend the life of infrastructure reliably (

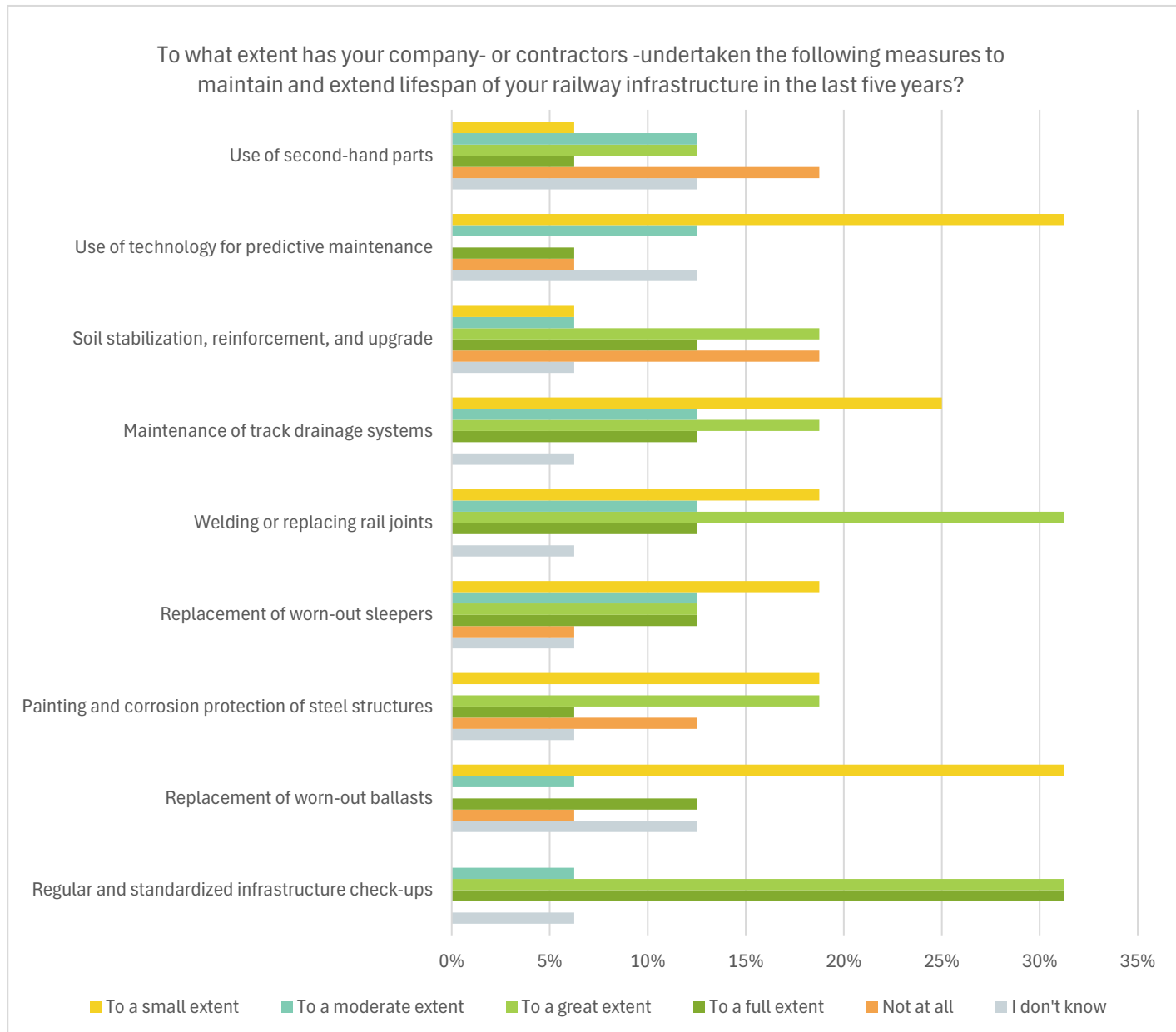


Figure 9). The same applies for catenary infrastructure PTOs as well. This is logical as it is often a contractual obligation on both the PTOs and the contracting parties involved to do regular maintenance of the infrastructure.

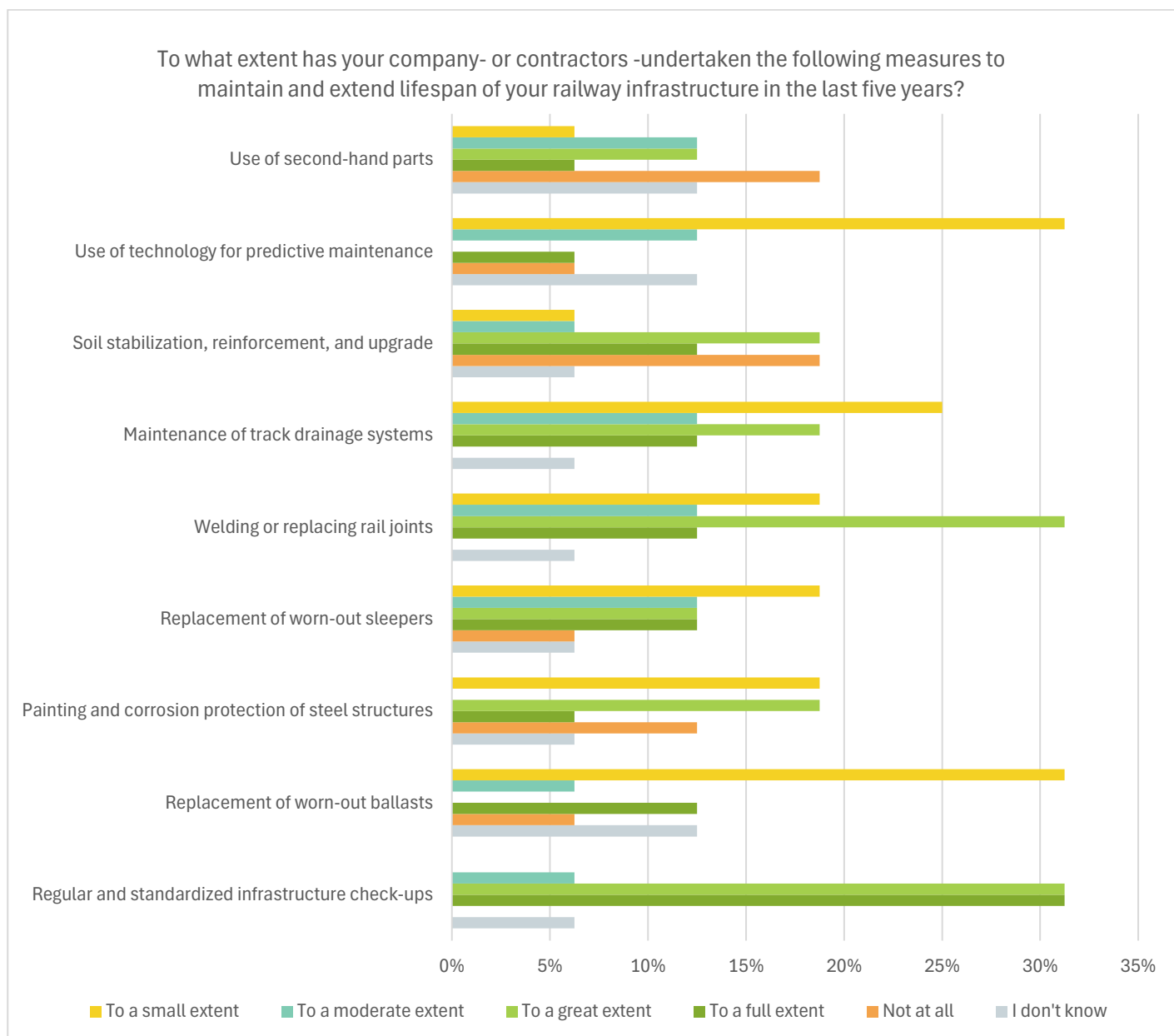


Figure 9. Key measures implemented to extend the lifespan of rail infrastructure

Insights related to buildings are similar in that most of the infrastructure dates back several decades and is not in the best condition due to age. However, PTOs have highlighted **efforts to specifically improve operational efficiency** by replacing old heating, air conditioning systems, and lighting, as well as making internal adaptations to meet changing requirements. This can be substantiated by the fact that more than 35% survey respondents did agree that the PTOs prioritised improvement of thermal and ventilation systems in their new and old building stock over the past five years.

However, PTOs do not report **major, in-depth, retrofitting to improve thermal performance in the existing building stock**, primarily due to costs. As one PTO respondent highlighted, their



estimates suggest that it is often more cost-effective to demolish and rebuild than to retrofit existing buildings, and that they are oftentimes other higher priorities than improving such facilities. The PTOs also fall behind in terms of adopting building certification standards such as LEED or BREEAM that can contribute to circularity, with all survey respondents reporting being unaware or not doing the same. This could be a potential area for improvement, as the need for certification standards is a feasible step that could be incorporated into the tendering process for construction and maintenance of existing and new buildings. In a workshop to validate the circularity indicators proposed as a part of this project, the partner PTOs validated this strategy to be “practically implementable” and “trackable”.

Reuse and recovery activities

A positive aspect, which may not be immediately apparent, is that reusing significant amounts of materials is already a common practice, especially within railway infrastructure. More than 30% of the survey respondents agreed to reuse and recovery of old rail components to a great extent over the past 5 years. Materials such as ballast, sleepers, and catenary switches are regularly reused, often with some level of repair or improvement to make them fit for use again. For example, one representative shared the case of a 50 km railway segment that was recently refurbished by repurposing components from national rail networks. This approach allows components that can no longer meet the demands of heavy-duty national operations to be transferred to local lines, where the requirements are less stringent.

However, PTOs emphasized that, **extensive reusing practices are oftentimes driven more by necessity due to remaining funding constraints rather than a deliberate commitment to sustainability or circularity.** The availability of financial resources varies by region, with local funding playing the most significant role. Meanwhile, state or national transfers remain uncertain, as they are often subject to political shifts and competition from other sectors.

Spare parts availability and extended supplier warranty

Another critical challenge highlighted by PTO respondents in extending the lifespan of infrastructure is the **ever-constraining lack of support and spare parts availability from suppliers.** This issue arises for various reasons, including providers and spare parts disappearing from the market, as well as more restrictive conditions that hinder in-house repairs or repairs by third-party providers while also reducing warranty periods.

One operator mentioned a case involving a digital spare part for tramway infrastructure, where the supplier has consistently reduced the warranty period from 20 years to 10 years, with plans to



further decrease it to 5 years. In response to this constraint, the operator had to become creative and to find workarounds to find and fix spare parts needed such as partnering with smaller companies to recreate and repair the component, even if it means losing access to software updates.

3.4. Transform stage

Status-quo on recycling and disposal strategies

Overall, it appears that recycling rates of materials and assets from public transport infrastructure are lagging. There are various reasons for this, but a common and straightforward one is that most recycling activities fall outside the PTOs' scope and are delegated to third parties who have the final say on how materials are handled. As a result, PTOs typically have limited agency and knowledge when it comes to ensuring and enforcing proper recycling practices. **This fragmentation and lack of knowledge and collaboration across the different value chain actors** may be posing a significant hindrance.

Other aspects highlighted include transportation issues and unclear guidance on how to manage the recycling of all materials produced by their activities. More than 30 percent of the survey respondents in the rail domain termed recycling to be a complex and intricate process that was time and human-resource consuming. However, several components in the rail infrastructure are very often recycled or repurposed through third parties.

Majority of the participants in the electric infrastructure domain cited **unclear recycling guidelines and protocols** and **insufficient recycling services providers in local context** as two challenges (Figure 10Error! Reference source not found.) in addition to the ones faced in rail infrastructure. Nevertheless, all PTO representatives reported to be aware of the need of recycling and considered it as a priority, with a sense of urgency attached to the same.

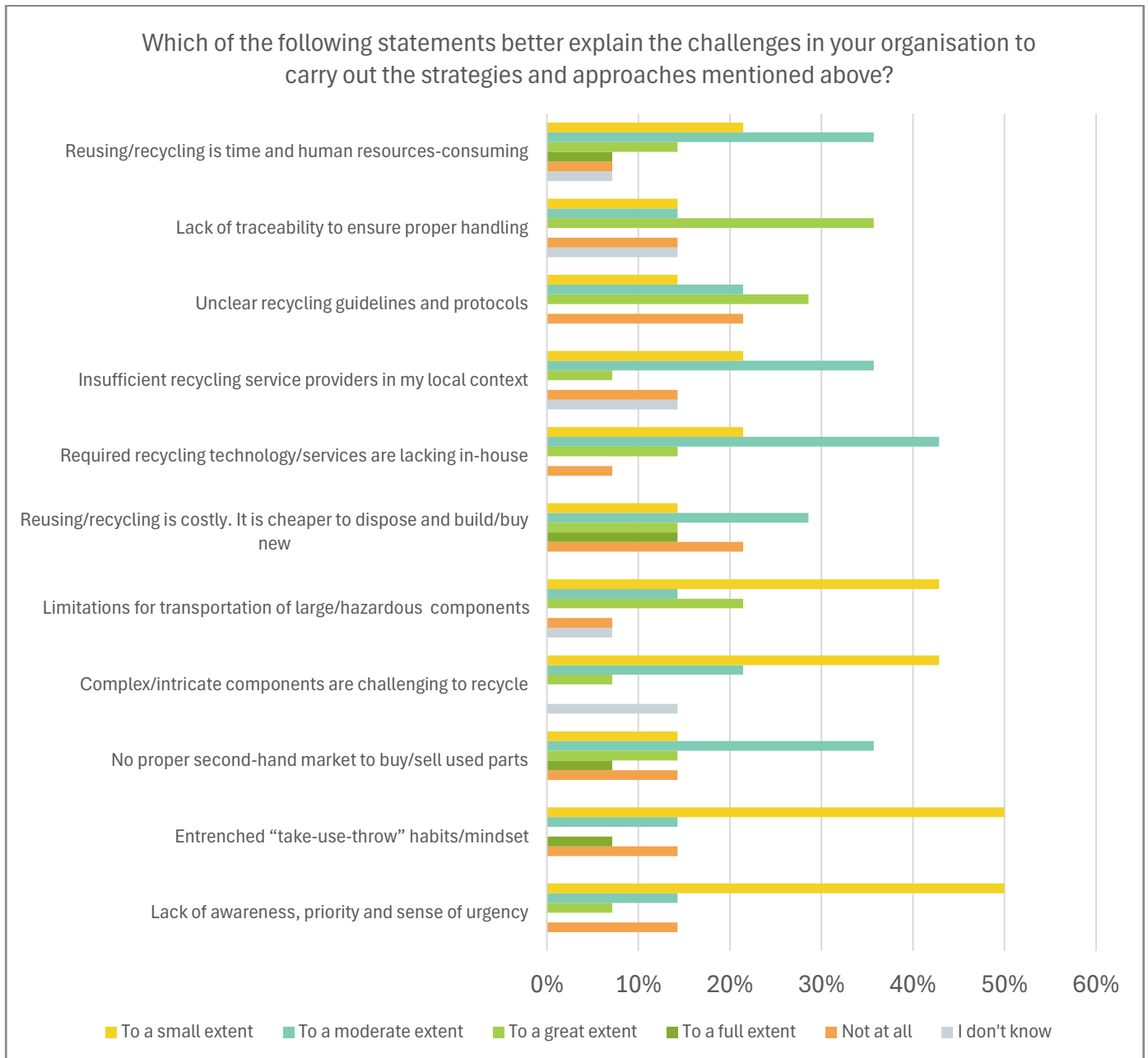


Figure 10 Key challenges faced within the 'Transformation' phase of catenary infrastructure

According to the survey results, majority of the respondents reported of proper disposal of hazardous materials always across rail and catenary infrastructure. Most survey respondents also agreed that many a times, the disposal or recycling activity happens within the city or regional borders.

Recycling and disposal analysis for selected materials

However, recycling activities for materials with high performance mostly depend on the type of material and asset. Exemplary cases of **high recycling levels** are metals, particularly those from



railway and catenary infrastructure, such as steel and copper. For instance, more than half of the respondents in rail infrastructure reported that at least 75% of steel was being recycled at the end of their lifespan (Figure 11). The same holds for copper in the case of electric infrastructure (Figure 12Error! Reference source not found.). Specifically, for these two types of materials, PTOs indicated that there are well-established partners in the market who specialize in recycling them, as they are commercially valuable and easily reintegrated into the value chain. In exchange for providing metals for recycling, PTOs receive monetary compensation.

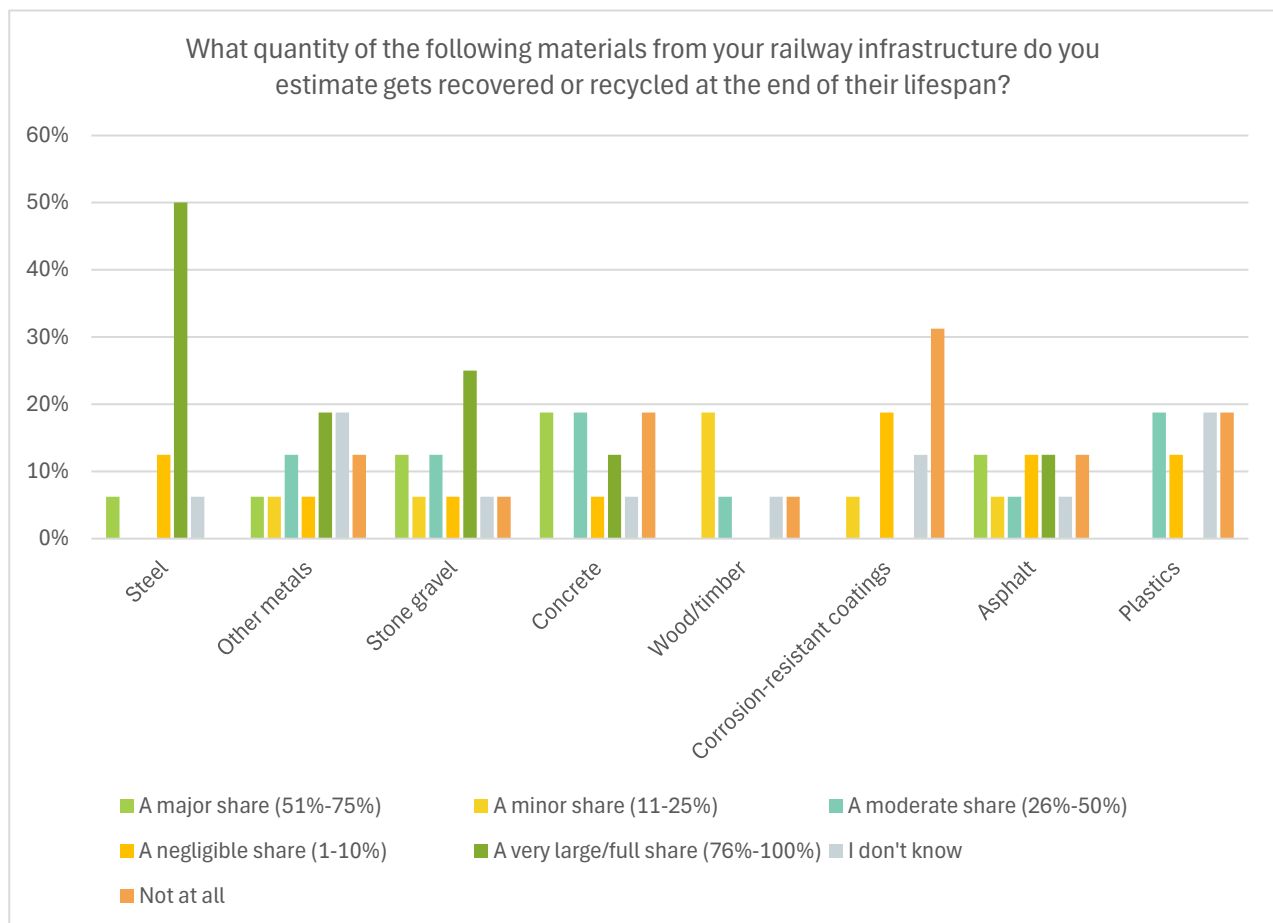


Figure 11 Quantity estimation of recycling or recovery of various materials in rail infrastructure

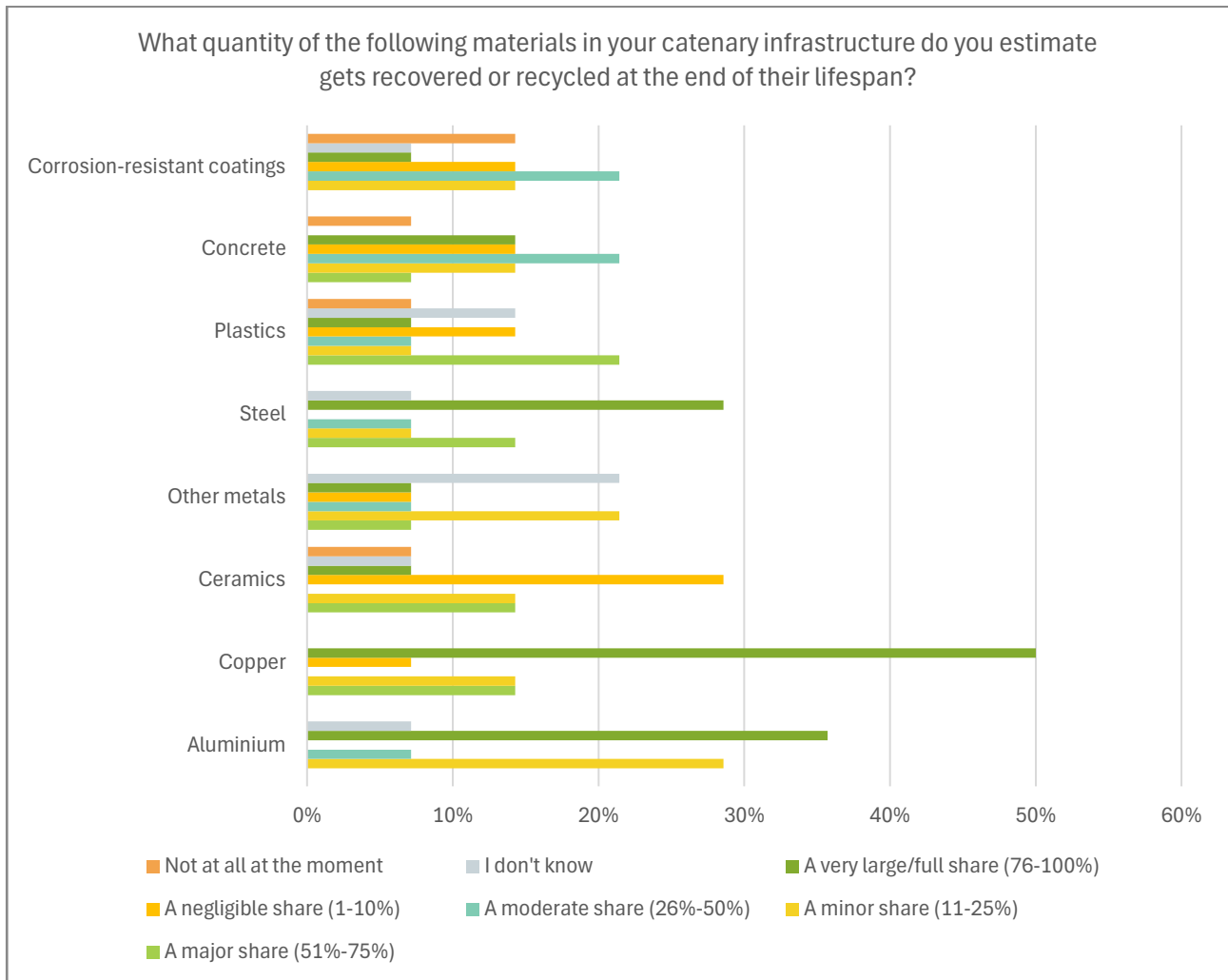


Figure 12: Quantity estimation of recovery or recycling of various materials in catenary infrastructure.

For other materials, **recycling is possible but less convenient, both logistically and economically**. A notable example from railway infrastructure is ballast. Used ballast can be recycled, but it requires a process of separating the large, reusable stones from the crushed and smaller particles that can no longer be used for railway purposes, as well as some cleaning. Only about 20% of the respondents reported of being able to recycle the stone gravel used. Experiences from PTOs vary; some engage in this process, while others do not, as obtaining new ballast—at least until recently—was cheaper than recycling the old material.

At the lower end, **the major recycling challenge is the waste generated from the demolition of buildings**, which is even more difficult for PTOs to influence as these activities are fully delegated to external parties. In many cases, PTOs are not the owners but the users or renters of the facilities. More than 30% of the survey respondents reported that the old or defective materials from buildings were rarely or never recycled either in-house or outsourced to third parties. Less than 20% reported of repurposing the buildings for other activities such as for storage and



warehousing. Only less than 20% respondents reported any substantial rates of concrete being recycled. These responses are illustrated in Figure 13.

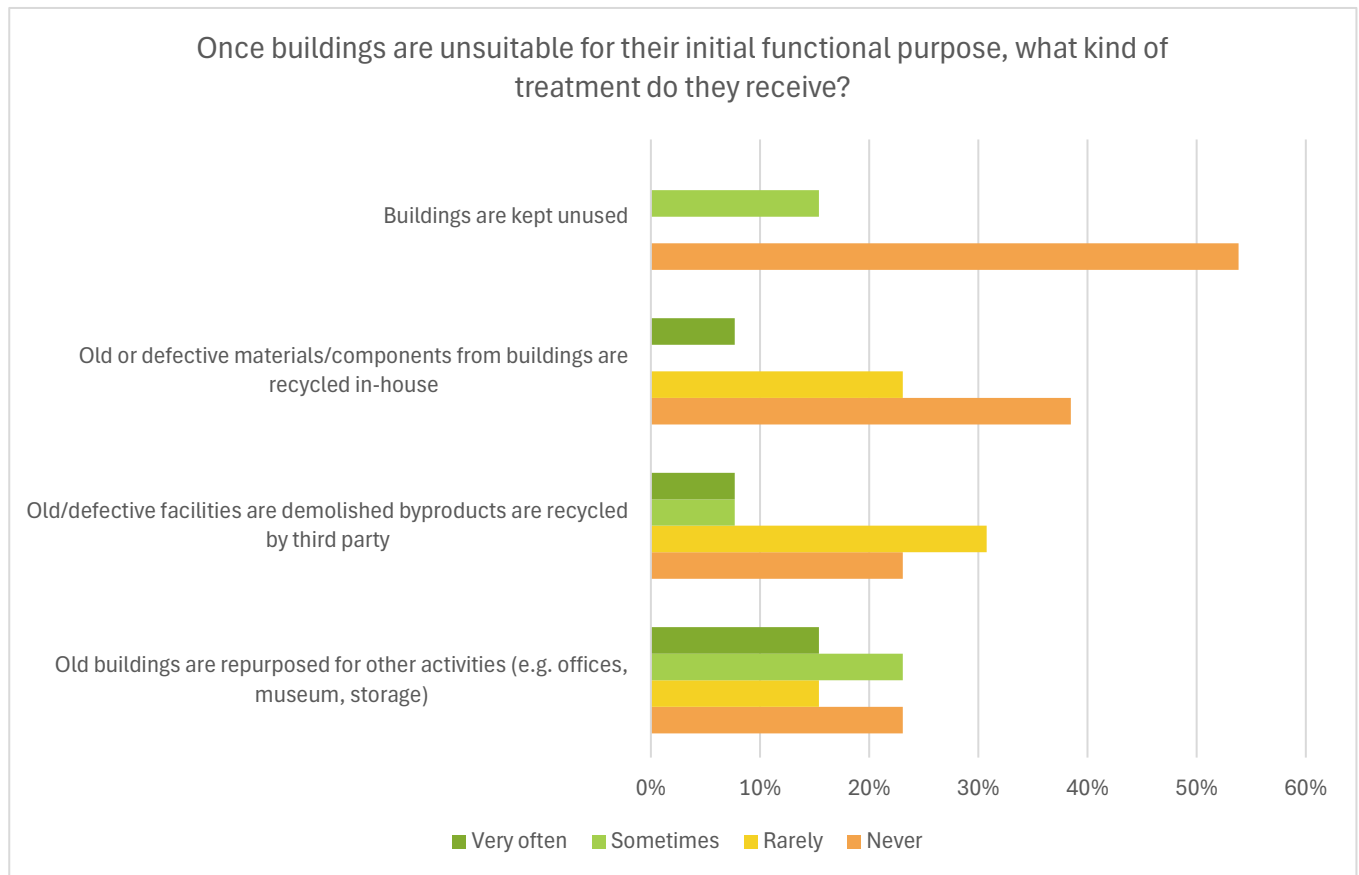


Figure 13: End of life strategies adopted for buildings by PTOs

A particularly critical material is concrete, which is ubiquitous in buildings and has low recycling rates. This is due to factors such as contamination with other materials, the combination of various components, and the challenges associated with efficiently recycling and reusing it.

Despite these challenges, one of the PTOs interviewed mentioned that they are becoming proactive in collaboration with other municipal companies to **process end-of-life materials in-house** by setting up recycling areas, equipment, and processes. This approach aims to increase recycling rates while ensuring transparency in the recycling process, ultimately aligning with the sustainability goals and commitments made by the city.

An interesting and somewhat different case was mentioned by one representative, who explained that since the public transport company is part of a conglomerate of public companies—including other essential utilities such as water and energy—these entities have a long-standing tradition of close collaboration and resource exchange. This governance model has led to the identification of cross-cutting key goals and activities, one of which has resulted in the establishment of dedicated recycling processes and facilities, enabling on-site recycling whenever feasible. Ultimately, this



approach has helped increase recycling rates and promote a more mindful use of resources within the company.

3.5. Enable stage

Regulatory and organisational insights

Although the Circularity Compass self-assessment includes a standalone section on governance aspects, this section was not requested when reaching out to respondents. Instead, input was gathered from cross-cutting areas in the survey and, more notably, from insights derived from the interviews.

From the interviews, it can be said that the circularity mindset is becoming more ingrained in public transport organizations (PTOs), increasing their interest in adopting circular economy practices due to a range of factors.

One clear factor mentioned by respondents was **the impact of European, national, and state policies on sustainability in driving change**. This was implicitly highlighted when participants listed measures such as finding ways to increase material reuse rates in order to comply with regulations. However, respondents also mentioned the complexity and **lack of clarity in certain regulations requirements**, particularly in finding clear protocols and methods for monitoring and reporting.

Another enabler identified is **the strong maintenance and upgrade expertise within organizations**. Specifically for respondents from Central Europe, this can be historically explained, as most assets—both buildings and railway systems—originated from the Eastern Bloc era, a time when spare parts were scarce, and market access was highly restricted. As a result, operators had to rely on upgrading, repairing, and restoring components. This practice has endured in many companies, with a significant number of processes managed in-house. However, **the challenge now lies in the generational shift**, which could lead to a potential shortage of personnel with the necessary knowledge and expertise.

Scope of digital solutions in circularity

Another enabler that was highly emphasized during the interviews is the potential of **using technology, i.e. digital tools, and AI as powerful allies to advance circularity in infrastructure**. Specifically, the PTOs expressed enthusiasm about the tangible possibilities and concrete impact these technologies could have, especially as automation levels continue to rise. Technology can be effectively leveraged, for example, to detect and respond in real-time to infrastructure issues,



minimizing downtime, saving time, and conserving resources. Additionally, approaches like digital twins are seen as highly beneficial for detecting and analysing energy flows in systems such as trams and trolleys. These tools help identify potential pitfalls, optimize energy use, and even uncover opportunities for additional initiatives, such as harvesting otherwise wasted energy to power vehicles and other devices or facilities.

Some general challenges in implementing circularity

Despite several opportunities mentioned, participants also identified constraints that are structural barriers to fully implementing the circular economy in public transport infrastructure:

Limited and inconsistent funding was consistently mentioned as a major challenge in advancing circularity in infrastructure. On one hand, there is a lack or inconsistency of support from national or state governments for local transport, leading to a reliance on local funding. However, local funding is not always secure or consistent, meaning all budget streams are subject to changes in administration, political shifts, and bureaucracy. Budget confirmations or project deliveries can also be delayed, and in the worst-case scenario, cuts may occur. More than 35% of the respondents in both the rail and electric infrastructure domain cited “**lack of funding**” and “**cumbersome permitting processes**” as two key challenges faced at the decision-making level in implementing circularity measures (Figure 14).

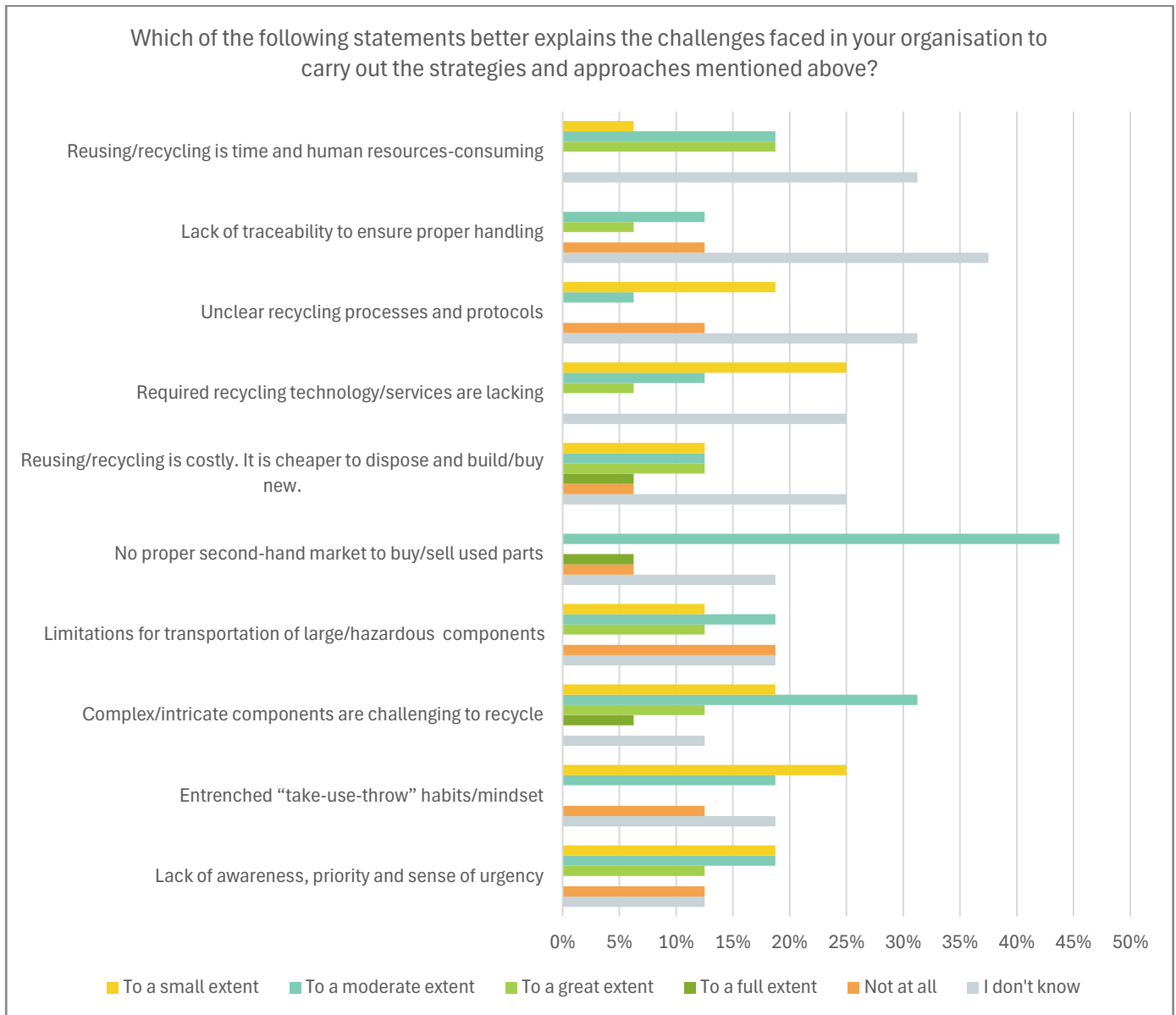


Figure 14. Challenges in implementing circularity in rail infrastructure by PTOs

A combination of financial and bureaucratic constraints is especially critical for public transport infrastructure, which requires long-term planning. As an alternative, PTOs resort to carrying out minor short-term upgrades, potentially delaying or neglecting major improvements.

Another challenge, within the organizational front, is that the companies often work in silos (Figure 14). This is particularly applicable for big PTOs with several modes and departments sprawled across different domains. Different departments—such as planning, procurement, operations, maintenance, and finance—often operate independently with limited coordination or shared objectives related to circularity. This fragmentation hinders the integration of circular economy principles across the asset lifecycle, as decisions made in one department (e.g.,



procurement of materials) may not align with long-term sustainability goals managed by another (e.g., maintenance or end-of-life disposal). Lastly, a significant challenge highlighted by one of the respondents interviewed is the **overwhelming impact of current economic and market trends**, in which planned obsolescence, reduced warranty times, and fragmented supply chains—often sourced from overseas—are the norm. In the respondents' view, the circular economy can realistically offer some alleviating and cost-effective solutions in certain cases, but structural change often feels like swimming against the current. In this context, PTOs perceive that driving significant change on their own is unfeasible, and that doing so will require bold policymaking, both at the national level and specifically at the EU level.

4. Approaches to advancing circularity in public transport infrastructure life cycle

After outlining the current state of circularity in public transport infrastructure, this chapter explores proactive strategies to accelerate its adoption. It covers both tangible solutions to specific challenges and broader, holistic approaches such as innovative regulations, integrating circularity into operational processes—such as tender documents and procedures—and platform for fostering cross-sector collaboration. Each measure includes a brief description and, where possible, examples of direct implementation or potential adaptation to public transport infrastructure.

As with the status quo analysis, this chapter follows the AETE framework, using the circularity principles measures diagram as a foundation. In line with the Circularity Compass, the AVOID stage is prioritized as the most cost-effective, ensuring mindful resource use from the outset. In second place, the EXTEND stage focuses on maximizing resource lifespan, while TRANSFORM serves as a last resort when other strategies are exhausted. Additionally, this chapter highlights ENABLE as a cross-cutting stage essential for sustaining long-term change through cooperation, knowledge-sharing, and evidence-based decision-making. Some measures may apply to multiple stages; for clarity, they can be explicitly mentioned and assigned to a specific section.

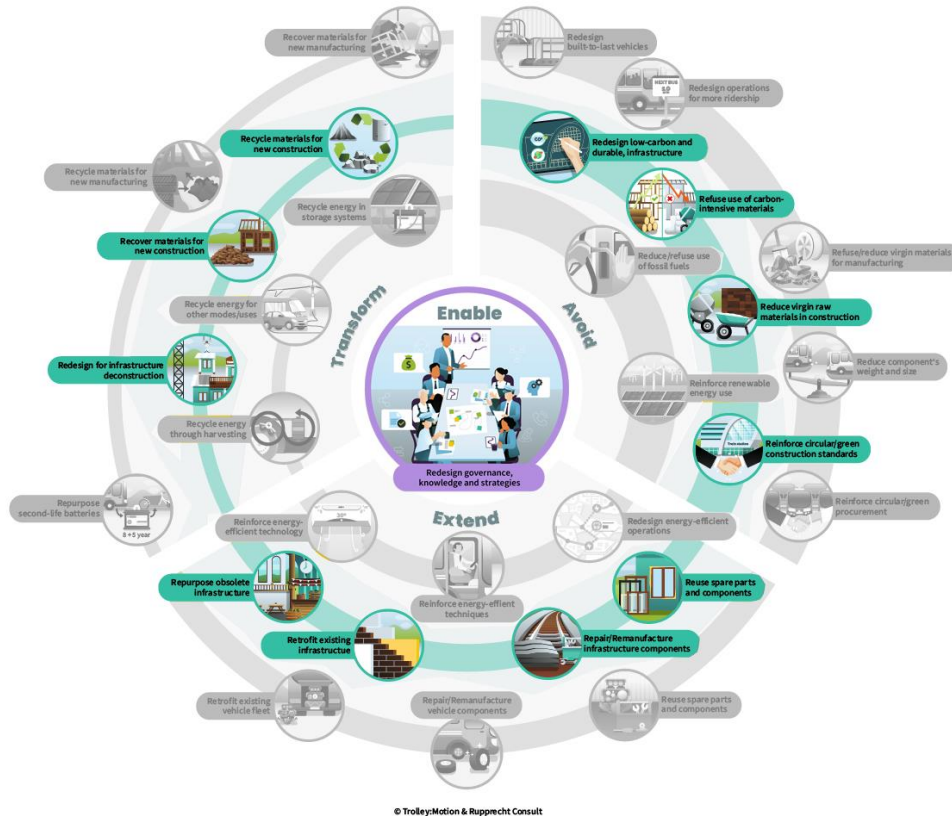


Figure 15 Circularity compass solutions diagram with a focus on PTI actions across the LCA

4.1. Approaches and solution at the AVOID stage

4.1.1. (Re)design low-carbon, durable infrastructure from the outset

Designing transport infrastructure with a circular approach from the outset is an indispensable decision. This stage largely determines the following stages of a product's lifecycle, for instance, whether a component can be repaired and maintained over a long period and whether materials can be easily recycled with minimal energy and effort.

Three principles need to be enforced when designing circular public transport infrastructure:

- **Design for longevity:** A well-thought-out design ensures that infrastructure and its components can be easily repaired, upgraded, or repurposed. As a general rule, infrastructure components should be of excellent quality to minimize repairs. It is also important to consider that these elements should allow for easy dismantling, be replaced for available options on the market, be repairable mostly by in-house or local technicians, and have a clear instruction for dismantling and recycling.



- **Design for minimal material use:** A critical aspect of circular design is rethinking resource consumption in construction, ensuring that only the necessary amount is used, eliminating redundancies, and finding innovative ways to maximize efficiency. Design approaches at the structural stage, for example, can help reduce the span and size of the columns in a building while maintaining its structural integrity. It is also important to opt for lighter solutions when defining material details.
- **Design for infinite material loops:** Last but not least, it is critical to abandon the concept of “waste” and instead treat materials as valuable resources that will be circulated indefinitely. This stage needs to ensure that materials are deployed in a way that minimally compromises capacity to be repurposed for future applications indefinitely.

Examples of circular construction are becoming more widespread, spanning residential buildings, schools, banks, and transport infrastructure. These examples demonstrate that dismantling preconceptions is possible, and that circular construction can be successfully applied in reality.

Lessons and inspiration from Triodos bank’s top-notch circular design



Figure 16 RAU Architects. Source: ArchDaily

The Triodos Bank Headquarters in The Netherlands is a great example of how circular construction can actually work in real life. Designed by RAU Architects, the entire building is fully demountable, meaning every part can be taken apart and reused. This principle could be applied to public transport infrastructure, especially when designing stations, depots, and waiting areas that can be easily updated or repurposed instead of being demolished.

Another interesting feature is that they used natural, non-toxic, and locally sourced materials to reduce environmental impact while maintaining structural integrity. This could be applied in public transport projects by using recycled or upcycled materials and prefabricated components that can be repurposed or reused elsewhere later.

Additionally, the Triodos Bank integrates nature into its design, such as maximizing natural light, energy efficiency, and green spaces. Public transport hubs could do the same by adding green roofs, better insulation, and water-saving systems to make them more sustainable in the long run.

This project proves that circular design is possible and not just a theory—it’s something that could really change how we think about building and maintaining public transport infrastructure. By



integrating these concepts into public transport infrastructure, cities can enhance sustainability, reduce lifecycle costs, and support a resilient urban mobility system.

Source: https://www.archdaily.com/926357/triodos-bank-rau-architects?ad_source=search&ad_medium=projects_tab

4.1.2. Refuse use of carbon intensive materials

A combination of traditional and modern construction techniques, along with technological advancements, is driving the shift toward low-carbon and recycled materials in construction—and, by extension, in transport infrastructure. For example, timber is increasingly used for buildings' structural elements and finishes, and natural fibres for insulation panels. and green steel for rail frameworks—debunking concerns about structural integrity, fire resistance, and high costs.

While PTOs and PTAs do not typically manufacture or construct transport infrastructure directly, they play a crucial role in enforcing circularity at the demand stage. Large procurement orders can push suppliers toward sustainable practices. By providing incentives that encourage suppliers to use low-carbon materials such as wood, natural fibres, and green steel, the industry can accelerate the adoption of sustainable solutions.

Applications of low-carbon materials in railway infrastructure

Traditional material	Low carbon Alternative	Exemplary case
Virgin steel rails	Green/recycled steel rails	SNCF, France's national railway company, adopted eco-designed rails for nearly 80% of its new purchases. By sourcing recycled steel produced through two environmentally friendly methods: "short cycle"- using recycled scrap rails- and electric furnace steelmaking powered by renewable energy. These processes reduced CO ₂ emissions by 70% and energy use by 30%, compared to traditional industrial coke furnace methods, all while meeting strict safety and technical standards. Source: https://www.groupe-sncf.com/en/commitments/sustainable-development/eco-friendly-rails
Concrete sleepers	Composite/ recycled plastic sleepers	Network Rail in the UK is switching from concrete and softwood sleepers to composite sleepers made from recycled plastic waste like bottles and packaging. These sleepers resist rot, water, and chemicals, last three times longer, and are fully



		recyclable. The change saves around £3 million annually and supports the company's 2050 net-zero carbon goals. Source: https://www.networkrail.co.uk/stories/a-greener-railway-environmentally-friendly-sleepers/
Virgin ballast	Recycled ballast	Ballast is critical for track stability and usually used in massive quantities, about 2 tonnes or more per meter of track. SNCF Réseau renovates around 1,000 km of track each year. Traditionally sourced from quarries, ballast extraction carries a high environmental cost. To reduce this, SNCF Réseau recycles ballast on-site using high-performance cleaning and screening units mounted on work trains. These remove fine particles and organic matter, making the ballast reusable. The process cuts quarry extraction, transport emissions, and material waste. By 2025, 25% of ballast will be recycled, saving the equivalent of 40,000 truckloads and significantly reducing CO₂ emissions. Source: https://www.groupe-sncf.com/en/group/about-us/companies/sncf-reseau/ballast-recycling
Copper catenary	Recycled copper for catenary line	In 2024, La Farga, together with ProRail, Strukton Rail, and Railtech BV, announced at InnoTrans the launch of the first railway catenary system made from 100% recycled copper, branded as Genius copper. While large-scale implementation is still forthcoming, the system has already showed a 92% reduction in CO₂ emissions compared to conventional copper. This was achieved through a circular manufacturing process powered by renewable energy, eliminating primary copper extraction and using energy-efficient technologies such as heat recovery and electrified machinery—delivering full performance with minimal environmental impact. Source: La Farga - Genius Copper

Applications of low-carbon materials in public transport facilities



Figure 17 EBMT, Naples Central Station. Source: Paolo Fasoli. Photo via ArchDaily

The shift towards low-carbon construction materials in public transport infrastructure is gaining momentum, with timber, green steel, and natural fibres emerging as viable alternatives to traditional, carbon-intensive materials. These materials offer structural reliability, fire resistance, and cost-effectiveness while significantly reducing the environmental footprint.

For example, timber-based infrastructure is proving to be a durable and sustainable solution for railway stations. The Naples Central Station, designed by EMBT, incorporates glulam timber as a primary structural element, showcasing its viability in large-scale transport hubs. The architects maintained the site's pre-existing concrete structures but added wooden elements and vaulted canopies on top, creating a new organic piazza that blends modernity with sustainability. This approach not only preserves existing infrastructure but also introduces environmentally friendly materials, enhancing the station's appeal and functionality. The use of timber not only enhances the station's architectural quality but also ensures structural stability and durability. Timber's lightweight nature allows for faster construction, reducing overall energy consumption during assembly.

Similarly, Arup's research highlights timber's potential for railway platforms, station roofing, and pedestrian bridges, where its carbon sequestration properties help offset emissions. By integrating these materials into public transport infrastructure, cities can achieve lower embodied carbon, increased resource efficiency, and enhanced lifecycle sustainability.

Sources: <https://www.arup.com/insights/material-change-can-timber-play-a-role-in-sustainable-rail-infrastructure/>

<https://www.archdaily.com/970506/new-images-reveal-embts-timber-central-station-in-naples>

4.2. Approaches at the EXTEND stage

4.2.1. Reuse spare parts and components

Reuse refers to the practice of using materials again for the same purpose. In this context, the mindset shifts towards viewing transport infrastructure as material banks, where components are temporarily used but eventually relocated to other structures to fulfil a similar purpose.



In railway infrastructure, reuse is a well-established practice. Many elements already achieve high reuse rates, as they are transferred to other railway networks—often in conditions with less stringent requirements. The reuse rates for railway materials vary depending on the material type; for instance, most plain line rails are easily reused, whereas ballast has a lower recycling rate due to stone wear and crushing during use. Nevertheless, advancements in techniques and technology continue to improve reuse rates.

In the building sector, reuse is less mainstream, as buildings are generally less standardized than railway infrastructure, making reuse more complex. However, certain standardized materials—such as windows, doors, partition walls, and sanitary equipment—offer great potential for reuse. Other materials relatively modular and standardized material such as bricks can also be reused but pose greater challenges, in this case due to the effort required to sort and clean each piece, which is often contaminated with mortar and susceptible to damage. However, new initiatives are emerging, and reuse has the potential to increase with growing knowledge, improved protocols, and advancing technologies.

Re-use of Trolley bus Switches in Szeged, Hungary



Figure 18 Trolleybus in Szeged.
Source: SZKT

Public transport operator SZKT launched a circular economy pilot by replacing heavily worn trolleybus switches at high-traffic intersections with new units and relocating the used ones to low-demand areas. This approach ensures that critical network points operate with high-reliability components, while still-functional switches continue serving in less demanding locations. As a result, the system benefits from both improved reliability at key junctions and prolonged use of valuable materials, aiming to double the typical 15-20-year lifespan of components. The initiative reduces waste and offers a scalable model for sustainable asset management in electric public transport.

Source: https://circularity4publictransport.eu/best_practice/demonstration-on-how-to-prolong-the-lifespan-of-electric-public-transport-infrastructure-reutilizing-heavily-used-trolleybus-switches-in-szeged-hungary/

4.2.2. Reinforce use of predictive maintenance methods and technology

Advancing the circular economy in the rail sector calls for smarter, more resource-efficient strategies—and **predictive maintenance** is one of the most promising. Unlike corrective maintenance, which reacts after failure, or preventive maintenance, which follows a fixed



schedule regardless of actual need, predictive maintenance leverages **real-time monitoring** and **data analytics** to anticipate failures before they happen.

This approach has only recently become widely feasible thanks to rapid advancements in **sensor technology**, **AI**, **data storage**, and **computing power**. By continuously analysing multiple data—such as vibrations, temperature, or component wear—hardware and software systems can raise alerts when infrastructure elements show early signs of deterioration.

As predictive maintenance becomes more widespread, its contribution to a **circular economy** is becoming clearer. It enables timely interventions that **extend asset lifespan** while using fewer costs and materials, less energy, and reduced labour.

Digital tool for predictive maintenance optimization in Leipzig



Figure 19 LVB pilot project for CE4CE

The adoption of predictive maintenance in public transport infrastructure is changing how cities manage ageing assets, offering both cost efficiency and improved reliability. By combining sensor data, machine learning, and digital platforms, operators can detect early signs of wear and intervene before costly failures occur, therefore extending asset life while reducing service disruptions.

In Leipzig, the local transport operator LVB is testing this approach on tram tracks and switches. They have partnered with Deutsche Bahn and other stakeholders to install sensors that monitor vibrations and track conditions in real time. The system uses AI to analyse the data and alert maintenance teams exactly where and when something needs attention. That means fewer surprises, quicker repairs, and less disruption for everyone using the network.

What is especially promising is that this solution works with existing infrastructure, no need for major upgrades. Data from the pilot is also being shared across operators, creating a knowledge base that supports replication in other cities.

By moving from reactive to predictive maintenance, cities like Leipzig are showing how digital tools can help reduce resource consumption and costs by extending asset lifespans, and embedding circularity into the daily operation of public transport networks



Sources: https://circularity4publictransport.eu/best_practice/predictive-maintenance-for-infrastructure-digital-optimization-in-leipzig/

4.2.3. Developed unified bigger second- hand market

In Europe, both physical and digital market initiatives have been growing in the effort to reduce waste and realize the value of materials, with both the public and private sectors increasingly engaged. These circular economy efforts are already widespread in certain sectors, particularly in fashion and food.

In construction and mobility, initiatives are still under development but are expanding. Specifically, the transport sector has a solid history of trading second-hand rolling stock, and also infrastructure assets in a minor extent. However, there is still a preference for physical, more closed markets where well-established relationships and trust between buyers and sellers can be built. These markets also provide a space where assets can be inspected, ensuring quality assurance and preparation before purchase. That said, this model is limited to nearby areas and requires space and logistical effort.

To address these limitations, digital platforms have emerged and are gaining traction. Despite some scepticism and limited use, these platforms are expected to grow as both buyers and sellers build their reputations. This shift holds immense potential to ease transaction processes, expand the supply and demand geographical scope, and facilitate the trade of more diverse assets.

Selected compilation of second-hand market initiatives in Europe

Name

Description

Whitemoor facility



Figure 20 Whitemoor facility.
Source: Source: Network Rail
(2019)

The Whitemoor facility in the UK, run by Network Rail, is a strong example of a physical second-hand market in the rail sector. It recovers railway components, like tracks and signals, from across the country, refurbishes them if needed, and redistributes them to sites where they can be reused. This helps cut costs and reduce waste. While the process is efficient and localized, similar facilities remain rare across Europe, despite their clear potential for broader use.

<https://www.networkrail.co.uk/stories/recycling-recovered-railway-materials-at-our-whitemoor-facility/>

DuSpot



Figure 21 Digital platform.
source: DuSpot

DuSpot is a Dutch digital platform that facilitates the exchange of residual construction materials and by-products such as soil, sand, concrete, and asphalt. It enables suppliers to list surplus materials and allows potential buyers to search based on material type, quantity, location, and timing. The platform includes tools for traceability, environmental compliance, and documentation generation, supporting the integration of reused materials into construction workflows.

<https://www.duspot.nl/ons-verhaal/>

https://cityloops.eu/fileadmin/user_upload/Materials/Tools/Material_Banks_and_marketplaces/CityLoops_Tool_factsheet_-_Matching_platform_for_construction_materials_2023-01-20_1_.pdf

Concular



Figure 22 Reuse of old brick in new facade in Aachen. Source: Concular GmbH

Another example of an innovative digital second-hand initiative in the construction sector is Concular, a German platform focused on the reuse of building materials. What sets it apart is its integrated approach, combining pre-demolition audits, digital material passports, and a dedicated marketplace into one streamlined system. The platform identifies and tracks reusable components, such as bricks, doors, and flooring, before demolition, ensuring they can be catalogued, assessed, and redistributed for future use. In one project,



over 7,000 bricks were salvaged and reused, while 45 interior doors were dismantled and reallocated through the platform.

<https://concular.de/>

Another relevant resource is the *Analysis of Digital Trading Platforms for Reused Materials*, an outcome of the Interreg North-West Europe project. This document compiles over 25 digital platforms that support the trade of reused construction materials across Europe. It provides insights into each platform's function, user base, and geographical coverage, offering public transport operators a practical starting point to explore potential partnerships and integrate circular practices through digital cooperation.

https://vb.nweurope.eu/media/20549/ddc_analysis-of-digital-trading-platforms-for-reused-materials_summary-and-platform-list.pdf

4.2.4. Repurpose obsolete infrastructure assets and components

In the realm of transport infrastructure, certain assets—despite being in good condition—can become obsolete or redundant for their original purpose. This can happen, for example, to railways or stations that lose demand due to socioeconomic changes.

By embracing a circular mindset, these structures present not a challenge, but an opportunity for innovative repurposing. By thinking beyond transport, it is possible to identify ways in which these assets—or parts of them—can be adapted for cultural, leisure, commercial, or residential purposes, meeting a demand for structural elements or space. Repurposing, whether fully or partially, not only reduces the environmental footprint by avoid unnecessary new construction but also by further extending the lifecycle of existing infrastructure that might otherwise deteriorate or be demolished along with the significant environmental costs of dismantling, recycling, or landfill disposal.



Repurposing old railway for less demanding transport activities



An innovative example of repurposing old railway infrastructure is seen in the Severn Tunnel project in Wales, where old track material that was once destined for disposal has found new life at the Global Centre of Rail Excellence. Instead of scrapping these materials, they were repurposed for less demanding rail activities, such as testing and development, reducing both the environmental impact and the cost of new infrastructure.

Figure 23 Severn Tunnel. Source: Network Rail Media Center

Old tracks can be relocated to less-frequented lines or sidings, where they serve secondary functions such as maintenance access, storage, or serving light-duty trains. This approach not only extends the lifespan of otherwise obsolete infrastructure but also contributes to resource efficiency by preventing waste and minimizing the need for new materials. Moreover, this practice demonstrates that even aged infrastructure can be adapted and utilized in a way that supports ongoing transport functions without necessitating costly new construction.

Such initiatives offer valuable insights for the public transport sector, showing how unused or obsolete assets can be transformed into functional components within less critical operations, thus contributing to the circular economy.

Sources: <https://www.networkrailmediacentre.co.uk/news/saved-from-the-scrapheap-old-track-from-severn-tunnel-gets-new-life-at-global-centre-of-rail-excellence>

<https://www.networkrailmediacentre.co.uk/news/saved-from-the-scrapheap-old-track-from-severn-tunnel-gets-new-life-at-global-centre-of-rail-excellence>



Repurposing of former railway station into a public library



Figure 24 State library in old train station. Source: Stadt Luckenwalde

An inspiring example of repurposing old infrastructure is the transformation of a former railway station in Luckenwalde, Germany, into a public library. This project transformed an underutilized transport asset into a vibrant community space, giving the station a new life and purpose. The renovation preserved the station's historic charm while adapting it to meet modern needs, making it a cultural hub that serves the local population.

The project was supported by EU funds, highlighting how circular economy projects can be financed through public funding. These funds enabled the repurposing of the building, ensuring that it continued to serve the community without requiring the construction of an entirely new facility. This approach not only conserved resources but also avoided the environmental impact of demolishing and rebuilding.

Sources: <https://www.brandenburg-tourism.com/poi/flaeming/historic-monuments-and-sites/luckenwalde-town-library/>

Repurposing old concrete ties as charging poles



Figure 25 Recycled concrete polls. Source: Deutsche Bahn

Deutsche Bahn has implemented an innovative pilot project in Berlin, that repurpose old concrete railway ties for use as solid foundations for electric car charging stations. These heavy-duty elements, once used to stabilize rail tracks, remain structurally sound even after their original service life and are well-suited to support EV chargers. This approach avoids the need for newly manufactured foundations, reducing both material consumption and construction waste.

The initiative was developed by DB Bahnbau Group and first implemented during the summer of 2024. It aligns with Deutsche Bahn's broader sustainability goals by integrating circular economy principles into



infrastructure development. Plans are underway to expand the project to other sites, demonstrating how aging transport components can be reused in ways that support emerging green mobility systems.

Source: <https://nachhaltigkeit.deutschebahn.com/en/measures/recycling-ties>

4.3. Approaches at the TRANSFORM stage

4.3.1. Recycle components for new use

Recycling takes place when (1) materials or components reach the end of their life, meaning they can no longer be used in their original form or for their original purpose, and (2) a transformation process is required to convert them into a different material or product. Recycling, therefore, requires energy, human resources, and well-coordinated processes from the source to the final product, making it a costly and resource-intensive activity. In transport infrastructure, several variables must be considered to assess the recyclability potential of materials and components.

- **Resources required:** Recycling demands energy and resources, depending on the level of sophistication needed. For example, if a material requires high amounts of energy to be melted down, this increases CO₂ emissions and energy consumption, especially if the energy source relies on burning fossil fuels.
- **Material purity level at the source:** The level of purity plays a significant role in recyclability. If a material is combined with other substances or integrated within another product, it becomes harder to separate and recover efficiently.
- **Resulting material quality:** Although materials can often be recovered, they may lose quality, making them unsuitable for their original purpose. In such cases, they are downcycled into lower-quality applications, or additional energy and resources are required to restore their properties.
- **Sorting process:** Recycling heavily depends on an efficient waste sorting system. In some cities and companies, this process is well-organized, while in others, it is poorly managed. Without proper sorting, recycling can be time-consuming and complex, requiring additional energy and resources.
- **Transport requirements:** Recycling may require materials to be transported over long distances, increasing costs, emissions, and energy use. Additionally, some materials require specialized equipment or vehicles for handling large or fragile parts, further complicating the recycling process.



Given the number and complexity of these variables, recycling should be considered a last resort—only after exploring more cost-effective and resource-efficient solutions such as reuse, repair, or refurbishment. Nevertheless, when planned and managed properly, recycling can still be a valuable solution.

Public Transport Authorities (PTAs) and Public Transport Operators (PTOs) are often directly involved in recycling processes but may face challenges in enforcing recycling measures. However, they can contribute in various ways, especially through procurement policies. They can mandate the use of recyclable materials in procurement, thereby driving demand for recycled products, or they can implement on-site recycling processes. Close collaboration and leadership from municipalities are also crucial. Municipalities can enforce recycling through regulations and programs for both the public and private sectors, such as requiring recycling quotas.

As a reference, the table below outlines the advantages, disadvantages, and recommendations for widely used public transport infrastructure materials, aiming to maximize benefits while minimizing the drawbacks of the recycling process. This can be useful for PTOs and PTAs when considering enacting recycling practices, either by taking tailored actions or by requiring them from stakeholders.

General considerations for the recycling and use of recycled materials			
Recycled material	Advantages	Disadvantages	Recommendations
Steel	High recyclability: Steel is 100% recyclable without loss of properties or need for virgin material. Source: Steel and the circular economy	Export challenges: Significant amount of EU steel scrap are exported, limiting domestic recycling benefits. Source: EUROFER	Policy measures: Implement incentives to retain steel scrap within the EU to support local recycling industries. Source: EUROFER
Copper	Energy efficiency: Recycling copper saves up to 85% of the energy compared to primary production. Source: euric_metal_recycling_factsheet.pdf	Collection inefficiencies: Inadequate collection systems lead to loss of recyclable copper. Source: euric_metal_recycling_factsheet.pdf	Infrastructure Improvement: Enhance collection and recycling infrastructure to maximize copper recovery. Source: euric_metal_recycling_factsheet.pdf



Plastics	Waste reduction: Recycling plastics can significantly reduce landfill use and environmental pollution. Source: Circular Plastics Alliance - Roadmap to 10 Mt recycled content by 2025	Quality concerns: Recycled plastics may have variable properties, affecting their suitability for infrastructure applications. Source: Circular Plastics Alliance - Roadmap to 10 Mt recycled content by 2025	Standardization: Develop sector and application related standards to ensure the quality and safety of recycled plastic materials in infrastructure. Source: Circular Plastics Alliance - Roadmap to 10 Mt recycled content by 2025
Concrete	Structural Applications: RCA can be effectively used in various structural applications, including road bases and sub-bases, contributing to sustainable construction practices. Source: JRC Publications Repository - Use of recycled aggregates in concrete: opportunities for upscaling in Europe	Mechanical Properties: Recycled concrete may have reduced strength and durability compared to conventional concrete, necessitating careful mix. Market Uptake: Limited market demand and lack of established supply chains hinder widespread adoption. Source: JRC Publications Repository - Use of recycled aggregates in concrete: opportunities for upscaling in Europe	Technical Standards: Develop and implement standards to ensure the quality of recycled aggregates. Policy Support: Implement policies that encourage the use of recycled aggregates in public projects. Source: JRC Publications Repository - Use of recycled aggregates in concrete: opportunities for upscaling in Europe
Asphalt	Cost savings of 10-20% by replacing virgin aggregates and bitumen; Up to 25% CO₂ reduction and 30% less energy use; 90% of old asphalt can be reused, supporting EU circular economy goals. Source: EAPA	Performance risks at high RAP content, including reduced fatigue resistance and cracking potential. Quality variability of RAP stockpiles can complicate mix design and consistency. Special handling & tech required for processing, increasing complexity at asphalt plants. Source: EAPA	Research and Development: Invest in R&D to improve RAP processing techniques and performance outcomes. Promote RAP use through green public procurement and minimum recycled content policies. Source: EAPA



4.4. Approaches at the ENABLE stage

The measures mentioned above are more concrete and technical, but before implementing them, it is vital to embed a Circular Economy (CE) mindset within organizations. This should start with PTOS, PTAS, and public authorities, as they play a key role in driving change and encouraging adoption across other sectors. A structured change management approach is essential to ensure a smooth and effective transition.

4.4.1. Reinforce (and realise) the power of public procurement

Procurement is one, of not the one, most powerful tools to realise circular economy in PTI. It enables public authorities and transport operators (PTOs) to influence markets and encourage providers to move toward more innovative, sustainable, and resource-efficient solutions.

Before engaging in procurement, the first and most important step—aligned with circular economy principles—is to assess whether the acquisition of a new product or asset is genuinely necessary. This involves carefully considering whether existing resources could meet the need through reuse, refurbishment, recycling, or sharing across departments or organizations.

Only after a thorough assessment confirms that a new asset is necessary should procurement move forward. In such cases, it is recommended to take the following key considerations into account:

- **Prioritize environmental and circular performance before or alongside cost**
Move beyond lowest-price criteria by giving equal—or even greater—weight to environmental performance. Factors such as durability, use of low-carbon materials, reparability, and recyclability should be prioritized. Apply tools like Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) to evaluate overall value, not just initial expenditure.
- **Embed circularity criteria in tender specifications**
Integrate specific and measurable circular design requirements into procurement documents—such as the use of secondary materials, modular construction, ease of repair, and end-of-life recoverability. Award higher scores to suppliers offering innovative circular solutions, including closed-loop models, resource efficiency improvements, and the use of material passports.
- **Use flexible, innovation-friendly contracts and business models**
Avoid rigid, fixed-price contracts in areas where innovation is needed. Instead, allow flexibility to adapt to evolving technologies, material availability, or market conditions—



especially in long-term or pilot projects. Additionally, consider leasing or service-based models where suppliers retain ownership, encouraging durability, easy maintenance, and product recovery at end-of-life.

- **Engage suppliers early and enable collaborative procurement**

Conduct early market dialogues, co-design workshops, and supplier engagement sessions to align expectations, encourage innovation, and build shared understanding of circular goals. This strengthens trust and aligns interests between buyers and suppliers. Use pre-commercial procurement or innovation partnerships to co-develop solutions and phase in increasingly ambitious circular requirements.

- **Promote cross-authority and operator collaboration**

Encourage joint procurement, shared frameworks, and continuous knowledge exchange between public authorities, transport operators, and agencies. Coordinated action helps pool demand, reduce costs, improve supplier responsiveness, and accelerate circular innovation.

- **Leverage digital tools for transparency and material tracking**

Mandate the use of digital tools such as material passports, digital twins, or Building Information Modeling (BIM) to document material composition, track product status throughout its lifecycle, and support future reuse, repair, or recycling strategies.

- **Support local providers and industrial symbiosis**

Prioritize local and regional suppliers that actively contribute to circular systems—such as remanufacturers, recyclers, and component refurbishers. Strengthening these supply chains reduces environmental impact, builds economic resilience, and fosters innovation. Wherever possible, encourage industrial symbiosis, where the by-products or waste of one industry become valuable inputs for another, creating closed-loop systems that optimize resource use across sector

Net-zero energy innovation procurement for Supreme Audit Office building in Czech Republic

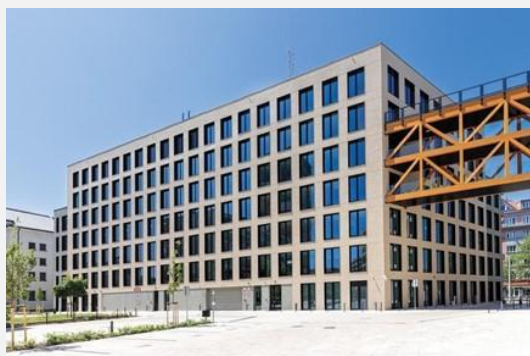


Figure 26 New headquarters of the Supreme Audit Office in Prague. Source: NKÚ

The Czech Republic's Supreme Audit Office (SAO) launched the construction of its first permanent headquarters with a clear goal: to deliver a nearly zero-energy building that would demonstrate how sustainable, cost-effective public infrastructure can be achieved through smart procurement. Instead of a conventional build, the project transformed a central Prague brownfield site into a high-performing administrative building, setting a new standard for public construction in the country.

The SAO used a Design-Build model under the FIDIC Yellow Book, with Building Information Modeling (BIM) as a central requirement. Bidders were evaluated 60% on cost and 40% on quality, including team qualifications and projected life cycle costs over 30 years. Bidders had to submit a BIM protocol and use materials with Environmental Product Declarations (EPDs). The tender also required environmental management measures and full compliance with national standards on air quality, acoustics, lighting, and thermal comfort.

Environmental results were tangible: 100 m³ of concrete and 8,000 m³ of sand were reused on site, and construction materials delivered by river reduced emissions by 22.5 tons of CO₂. BIM enabled efficient integration of heat recovery systems, green roofs, and adaptive façade shading. The project received a “silver” rating under the SBTool.CZ certification scheme, which evaluated comfort, material health, and urban integration. Additional user benefits include accessible design, bike charging, on-site childcare, and improved working conditions, making the building not just efficient, but truly people-centered.

Sources: https://green-forum.ec.europa.eu/green-public-procurement/good-practice-library/building-net-zero-energy-innovation-through-procurement-construction-headquarters-supreme-audit_en

Circular and energy-neutral innovation procurement for Cruquius Bridge replacement in North Holland



Figure 27 Provincie Noord-Holland. Source: European Commission

When the Province of North Holland began planning the replacement of the Cruquius Bridge, they knew a standard approach wouldn't deliver the long-term resilience they were aiming for. Instead of prescribing every detail in advance, they initiated a competitive dialogue process—an unusual move for a civil engineering project. Their ambition was clear: the new bridge needed to last 100 years, be energy-neutral during use, allow for disassembly and upgrades, and minimise environmental impact over its entire life cycle.

Three shortlisted teams participated in structured rounds of dialogue, allowing the province to test the feasibility of circular and sustainable solutions early in the design phase. The technical specifications required a modular structure based on the Dutch IFD (Industrial, Flexible, and Demountable) standard NTA 8086, with materials chosen for high-quality reuse. Bidders had to prove that structural elements could be dismantled without material loss and explain their reuse strategies using lifecycle assessments following EN 15804. Technologies had to be near market-ready (Technology Readiness Level 7 or higher) and fully implemented by project delivery. The bridge also had to operate without fossil energy and be designed for low maintenance. Award criteria were clearly defined: 55% of the evaluation focused on the “Plan for ambitions,” covering circularity, disassembly, and energy-neutrality; 30% on the “Plan for effective collaboration”; and 15% on the “Plan for the execution phase,” including risk management and planning.

The final design resulted in a bridge built with prefabricated, low-maintenance, and fully demountable components. Energy use is offset through integrated renewable energy systems. Beyond the physical outcome, the project demonstrated how public authorities can use dialogue not just to procure a structure—but to shape a shared process, strengthen innovation, and hold partners accountable to measurable, long-term sustainability goals. The Cruquius Bridge now stands as one of the clearest examples in the Netherlands of how procurement, when used creatively, can drive lasting environmental and technical value.

Sources: https://green-forum.ec.europa.eu/green-public-procurement/good-practice-library/competitive-dialogue-circular-and-sustainable-bridge_en



4.4.2. Build up the knowledge and collaboration

To establish and operationalize the Circular Economy (CE) within an organization or sector, one of the most effective strategies is to transition from somewhat individual projects and personal motivations to a structured, dedicated group. This core team would be responsible for establishing CE goals and targets, converging support and knowledge from different departments, producing and disseminating knowledge, and piloting and scaling solutions. Such a team could be embedded within sustainability and research departments, but it is important to maintain a strong focus on evidence-based planning and implementation—aiming to reduce life-cycle resource consumption and minimize ecological footprints.

SNCF Réseau



On its journey towards circular economy adoption, SNCF Réseau, the French national rail operator, has effectively implemented a knowledge-sharing strategy that encourages collaboration across departments. The company has created a dedicated sustainability team that drives circularity goals, focusing on evidence-based solutions and involving different departments in integrating sustainable practices into daily operations.

In addition to internal efforts, SNCF Réseau collaborates with external organizations, including research institutions and government bodies, to expand knowledge and share best practices. This network facilitates the development and scaling of innovative circular solutions, such as the use of recycled materials in rail infrastructure and repurposing older components. SNCF Réseau used professional uniforms to repurpose into a new life cycle through a comprehensive French recycling industry. The recycling process involves automated sorting, fabric shredding, and blending to create new yarn and fabrics for garment and travel bag production.

By building internal expertise and promoting external collaboration, SNCF Réseau is actively supporting the shift towards a more sustainable, circular economy in public transport infrastructure.

Sources: <https://www.groupe-sncf.com/en/commitments/sustainable-development/circular-economy>
<https://cdn.fs.agorize.com/DWfsNv69QYm72OezDiq2>
<https://www.groupe-sncf.com/en/commitments/sustainable-development/circular-economy>
<https://cdn.fs.agorize.com/DWfsNv69QYm72OezDiq2>



4.4.3. Leverage Building Information Modelling (BIM) technology for cradle-to-cradle infrastructure decision making.

Building on the previous measure, technology plays a strategic role in supporting circularity planning and decision-making. The advantage is that numerous solutions are available, some well-established and others continuously evolving. One of the key technologies that continues to expand and become mainstream is BIM (Building Information Modelling), which offers immense possibilities to facilitate circularity decision-making throughout all life cycles, from design to decommissioning.

Here is list of the possible benefits BIM can provide for advancing the circular economy in infrastructure:

- **Material efficiency:** Precise digital models that enable planning and estimation of the materials needed for construction during the design stage.
- **Material tracking:** Accurate estimations and informed decisions regarding quantity management, accurate ordering, and the prevention of overproduction.
- **Basis for more advanced circularity analysis:** A BIM model can serve as a foundation for in-depth bioclimatic and circular analysis to, for example, simulate thermal, lighting, and ventilation performance, enabling the design of more efficient resource use and a reduced ecological footprint.
- **Flexible and modular design:** BIM facilitates the design of components that can be easily adjusted to future needs, changes, and can be disassembled at the end of their lifecycle.
- **Lifecycle asset management:** BIM helps track an asset's lifecycle, from design to decommissioning. For example, it allows to provide regular updates on repairs, replacements, demolitions, or new additions, ensuring data is available.
- **Deconstruction and resource recirculation:** Data from the BIM model can be instrumental in planning an efficient deconstruction process. This data helps identify and sort materials for reuse, repurposing, or recycling, minimizing construction waste.

Railway Baltica: BIM for development of modern and sustainable railway infrastructure



Figure 29 Use of BIM in Rail Baltica project. Source: Rail Baltica

Building Information Modeling (BIM) is central to the delivery of Rail Baltica, a major cross-border railway infrastructure project connecting Estonia, Latvia, and Lithuania with the wider European rail network. RB Rail AS has implemented a unified BIM strategy from the early design stage, using it as the foundation for integrated collaboration, technical coordination, and digital asset management across the entire life cycle of the railway system.

The project applies BIM through a central Common Data Environment (CDE), where all disciplines—engineering, architecture, geotechnics, and environmental planning—contribute to and access shared models. Every physical element (stations, bridges, tunnels, utilities) is represented with geometry and metadata. Clash detection and spatial coordination are carried out before construction begins, reducing errors and redesign. Standardised file naming, data validation rules, and model development levels have been set across all countries and contractors. These practices ensure that design outputs are consistent and ready for procurement, permitting, and future operational use. RB Rail AS also publishes guidance on BIM roles, quality control, and data structures to align contractors and consultants.

The sustainability potential of BIM in Rail Baltica lies in its ability to support informed decisions early. For example, BIM models are used to track material quantities, improve scheduling accuracy, and evaluate long-term maintenance requirements. This supports the selection of durable, low-impact materials and minimises excess resource use. The structured data also lays the groundwork for digital asset management, enabling efficient maintenance, repair, and component replacement decades after construction. By embedding sustainability criteria into a common digital framework, BIM allows Rail Baltica to coordinate infrastructure development across three countries with efficiency.

Sources: <https://www.linkedin.com/pulse/tapping-potential-bim-sustainable-railway-infrastructure-development-ar2cf/>

https://www.railtech-europe.com/wp-content/uploads/2024/03/02.-BIM-for-Railways_-Enhancing-Design-Efficiency-Sustainability-and-Decision-Quality-Borja-Manzano-Hidalgo-and-Blanca-Ortiz.pdf

<https://www.railbaltica.org/rb-rail-as-bim-documentation/>
<https://globalbim.org/info-collection/rail-baltica-bim-documentation/>



4.4.4. Reinforce unified life-cycle data collection and analysis

Available, accurate, and unified data on the infrastructure life cycle is crucial for making informed decisions and streamlining processes. However, such data is currently scarce, poorly collected, and fragmented across different infrastructure stakeholders, each holding only partial information. Additionally, generating data retrospectively through, for example, material flow analysis can be costly and prone to inaccuracies.

In addressing this significant data gap, some stakeholders have already taken the initiative. For example, SNCF France developed **material identity sheets** to create a comprehensive inventory, enabling a better understanding of the quantity, dimensions, materials, and condition of 100% of the components in their railway infrastructure.

A growing and increasingly popular strategy for enhancing multi-sector life-cycle data collection is the **Material Product Passport**—a centralized, one-stop data hub that systematically gathers

Pioneering use of material passport at Edenica building in London



Figure 30 Edenica building. Source:
<https://constructionmanagement.co.uk/>

With the motto “pushing the boundaries of sustainability,” the developers of the Edenica 12-story office building in London have designed a top-tier sustainable design that, inter alia, reduces material usage, maximizes natural ventilation, insulation, and lighting, and includes rooftop solar panels and heat pumps for thermal comfort.

Remarkably, they have also pioneered the development of a material passport, detailing key building materials and components for the substructure, tiles, steel frame, and concrete panels, etc.

Using a “learning by doing” approach, they have defined the type of information to be included, set up a database and provide instruction on how to use and updates throughout different life-cycle stages. This system will improve future maintenance and upgrades and simplify material reuse at the end of building components’ life cycle.

The project applies BIM through a central Common Data Environment (CDE), where all disciplines—engineering, architecture, geotechnics, and environmental planning—contribute to and access shared



information on each relevant stage of a product's life cycle. In transport infrastructure this could include, but not limited to:

- Material inventory, specifying type, quantity, and embodied emissions
- Building permit details
- Energy performance data, including actual energy consumption and associated emissions
- Greenhouse gas emissions, converted from energy consumption
- Sustainability assessment results, including certifications or labels
- Evidence and description of maintenance and upgrade activities
- Instructions for dismantling and recycling at infrastructure components' end-of-life

Both the tool itself and the process of gathering data for it have the potential to significantly advance circularity decision-making across the entire infrastructure asset life cycle. For example, information on the embodied carbon of materials in the construction phase can guide the selection of more sustainable alternatives. Additionally, detailed insights into energy performance and thermal conditions can help prioritize actions during the refurbishment phase. Furthermore, comprehensive data on infrastructure component assembly, along with clear instructions for dismantling and recycling, can simplify material recirculation at the end of an asset's life.

This approach is already mandated under EU regulations, initially applied to specific products—such as EV batteries—with plans for expansion to other projects and sectors. While adoption remains limited and the technology is still evolving, the transport infrastructure sector is in the early stages of implementation. However, pioneering real-life cases are already shaping how material passports and protocols can support improved circularity and offer valuable insights for scaling up adoption.

Sources: <https://www.cibsejournal.com/case-studies/trialling-materials-passports-at-the-edenica-office-building/>

<https://nla.london/news/pioneering-use-of-materials-passports-at-londons-edenica>



5. Monitoring and evaluating circular economy in PTI

This section aims to provide a framework of indicators at the intersection of transport assets and the circular economy. Each infrastructure strategy will include its own list of indicators, with potential overlapping. It represents a curated yet evolving list of indicators, continuously refined based on new insights and practical experience. The list is not intended to be a fixed set of indicators, but rather a catalyst in the initiation of cross value chain conversations. It acknowledges gaps and the need for further discussion, aiming to serve as a foundation for dialogue, refinement, and harmonization with stakeholders across different scales—from individual companies to government policies.

5.1. Importance and scope of circularity indicators for public transport

For the effective implementation of the circular economy in any sector—especially in public transport infrastructure—an indicator-based monitoring process is essential. Circularity indicators play a pivotal role, primarily for public transport operators, and secondarily for policymakers, city planners, and transport authorities. These indicators help assess how effectively public transport systems are closing resource loops, minimizing environmental impacts, and promoting reuse and recycling, all measured against a set of predefined criteria. Without a clear and consistent set of indicators, progress toward circular economy goals remains vague, and the impact becomes difficult to track, improve, and ultimately realize.

To the best of our knowledge, limited work has been done in proposing a comprehensive set of indicators specifically addressing the relationship between public transport and circularity. Circularity indicators differ from conventional ones by focusing on how well transport systems manage the entire lifecycle of materials—reducing resource consumption, extending asset lifespans, and increasing the reintroduction of materials into the economy. However, this does not mean starting from scratch. In fact, public transport operators and other stakeholders have a well-established practice of tracking indicators such as fuel consumption, asset lifespan, and material recycling rates. These indicators, in turn, act as circularity metrics, offering valuable insights into resource usage, extension, and recovery. The approach followed to develop this list is to build upon what stakeholders—particularly public transport operators—are already typically tracking, and, where necessary, adjust or refine these metrics to better report on circularity. Although this is the "low-hanging fruit," the goal is not to remain there, but to raise ambition and broaden the scope. Therefore, we propose rating the indicators based on their scope:



A good starting point is the recent Bellagio Declaration, which was endorsed in December 2020 by the Heads of the Environment Protection Agency of Germany, France, Slovakia, Switzerland, the Netherlands, Austria, Italy and the European Environment Agency (EEA). According to ISPRA & EEA (2020), it is a set of principles on how to ensure that a monitoring of the transition to a circular economy captures all relevant aspects and involve all relevant parties.

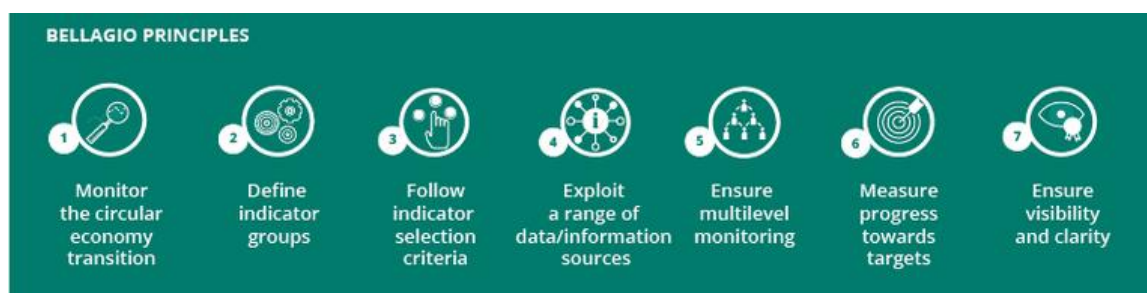


Figure 32 The 7 Bellagio Principles on Circular Economy indicators. Source: bellagio-declaration.pdf

Figure 32 describes the brief outline of the 7 Bellagio principles. Within the indicator development framework, it defines the following 4 indicator groups:

1. **Material and waste flow indicators:** To monitor changes throughout the material life cycle, including resource efficiency dimensions.
2. **Environmental footprint indicators:** To capture the impacts across the full life cycle of products and materials, ensuring that spill-over effects are assessed, and planetary boundaries are respected.
3. **Economic and social impact indicators:** These capture both positive and negative impacts that may occur during the structural changes of the circular economic transition.
4. **Policy, process, and behavior indicators:** These track the implementation of specific circular economy policy measures and initiatives.

Another popular indicator system is the European Circular Economy Monitoring Framework³⁴, established by the European Commission and Eurostat to monitor progress towards a circular economy using available statistical data. The key components of this framework include:

1. **Material footprint:** Measuring the total amount of raw materials used.
2. **Consumption footprint:** Assessing the environmental impact of consumption.

³⁴ European Commission. (n.d.). *Circular economy monitoring framework*. <https://ec.europa.eu/eurostat/web/circular-economy/monitoring-framework>

European Environment Agency. (n.d.). *Measuring Europe's circular economy*. <https://www.eea.europa.eu/en/topics/in-depth/circular-economy/measuring-europes-circular-economy>



3. **Circular material use rate:** Calculating the percentage of materials that are reused or recycled.
4. **Waste generation and decoupling:** Tracking the amount of waste generated and efforts to decouple economic growth from waste production

The next case in point is the Circularity Transition Indicators (CTI)³⁵ framework by the World Business Council for Sustainable Development (WBCSD). It was developed in collaboration with 50+ companies and organizations and aims to make a credible assessment of a company's contribution to circularity. The CTI assess the material flow within the company at three key intervention points:

Inflow Assessment:

- **Renewable materials:** It evaluates the percentage of materials entering the system that are renewable, meaning they can be replenished naturally over time.
- **Non-virgin materials:** It also measures the proportion of non-virgin materials, which are materials that have been previously used and recycled, thus reducing the need for new raw materials.

Outflow Assessment:

- **Recoverability:** CTI assesses how easily materials can be recovered at the end of their life cycle. This includes evaluating the design of products to ensure they can be disassembled and their components reused or recycled.
- **Actual recovery:** It measures the actual percentage of materials that are successfully recovered and reintroduced into the production cycle, rather than being disposed of as waste.

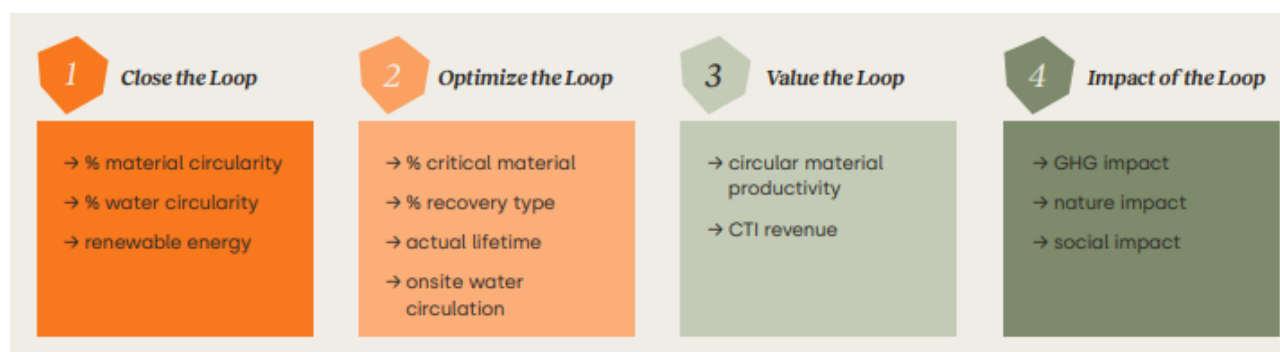


Figure 33: CTI indicators retrieved from CTI v4.0. Source: WBCSD_CTI_enabling_solutions.pdf

³⁵ World Business Council for Sustainable Development. (2025, March). *Circular Transition Indicators (CTI): Enabling solutions*. https://www.wbcsd.org/wp-content/uploads/2025/03/WBCSD_CTI_enabling_solutions.pdf



5.3. Evolving list of indicators for monitoring circularity in public transport

This section will present a non-exhaustive and evolving set of indicators that can be used to measure or assess the extent of implementation of circularity in the domain of public transport indicator. In alignment with the circularity compass, the indicators have been classified into the following categories:

AVOID (Upfront stage): These are indicators that assess the strategies aiming to promote circularity by avoiding the use of primary or virgin materials, unsustainable materials etc. They focus on the proportion of secondary materials, carbon-neutral products, and durable materials, promoting the use of resources that have a lower environmental impact and longer lifespans.

EXTEND (Operational stage): These indicators focus on the performance and efficiency of the infrastructure during its operational phase. They include metrics such as energy consumption, operational waste reduction, service life utilization, and operational emission intensity, aiming to optimize resource use, reduce waste, and minimize the environmental footprint of the infrastructure.

TRANSFORM (end-of-life stage): These indicators assess circularity by looking into the actions or strategies done on components at the end of their lifecycle. They include metrics such as the rate of recycling, reuse, repurposing, and repair, emphasizing the importance of extending the life of materials and reducing waste through effective recovery and reuse strategies.

ENABLE: These indicators evaluate the efficiency and sustainability of processes and systems used in public transport infrastructure. They cover the use of life cycle assessment tools, Building Information Modelling (BIM) for material optimization, and other practices that enhance resource efficiency and minimize environmental impact throughout the infrastructure's lifecycle.

In addition to the above categorisation, the indicators were also sorted according to the extent of trackability by the PTOs based on an indicator validation workshop, as described in section

It is important to note that the given categorization of circularity indicators is not set in stone. Different approaches can be used to classify and measure circularity in public transport infrastructure. The approach provided here is comprehensive and covers various aspects of circularity, but other approaches could also be equally valid. This flexibility allows for the adaptation of indicators to specific contexts and objectives, ensuring that the assessment of circularity remains relevant and effective.

Table 2: Non-exhaustive list of circular indicators for PTI

Indicators Category	Indicator	Unit	Description	Measurement Methodology	Data Required	Significance of the Indicator	Scope of Implementation for PTOs
Avoid	Secondary Material Input Ratio	%	What percentage of input materials (by weight, volume etc.) are secondary / non-virgin materials sourced from end-of-life scrap of internal or external sources.	Calculate the weight or volume of secondary materials used in construction divided by the total weight or volume of all materials used. This can be tracked through procurement records and verified by certifications or documentation from suppliers ³⁶	Inventory of feasible non-virgin or end of life materials available internally or externally, Historic data on performance of components with non-virgin materials	Encourages the use of scrap materials, reducing the demand for virgin resources and minimizing environmental impact.	Within Scope of PTOs, and the indicator is trackable.
	Circular Economy procurement or tendering	% or scoring index	Inclusion and enforcement of green and circular economy principles within the procurement and tendering procedures.	Proportion of tenders in which CE-related criteria are included as mandatory requirements, or preferential conditions.	Information on procurement policies, guidelines, data on contractual clauses enforcing CE-related outcomes, interviews with procurement	By enforcing CE principles at the procurement stage, PTOs can significantly influence supplier behaviour, drive demand for low-impact materials	Within the scope of PTOs, and the indicator is trackable.

³⁶ European Circular Economy Stakeholder Platform. (n.d.). *What role do secondary materials play in new constructions and buildings renovation?*
<https://circulareconomy.europa.eu/platform/en/news-and-events/all-events/what-role-do-secondary-materials-play-new-constructions-and-buildings-renovation>

				CE4CE	officers or auditors.	and technologies, and foster innovation across the value chain.	
	Low carbon material usage	%	What percentage of input construction materials (by weight, volume etc.) are low carbon, carbon-neutral etc. E.g.: Fly-ash based concrete, geopolymers concrete etc.	Calculate the weight or volume of low-carbon, durable materials used in construction divided by the total weight or volume of all materials used. This can be tracked through material procurement records and verified by Environmental Product Declarations (EPDs) or similar certifications ³⁷	Data on quantity and composition of materials used at various stages of construction.	This indicator supports circularity by promoting materials that have lower embodied carbon and longer lifespans, aligning with climate action goals.	Within the scope of PTOs, and the indicator is trackable.
Enable	Digital tools application	%	Proportion of construction and procurement processes executed with digital tools such as BIM, or LCA software used in circularity and resource use optimization.	Digital audits, knowledge dissemination workshops.		This indicator supports circularity by leveraging digital solutions to optimize material use, lifecycle management, and maintenance practices.	Within the scope of PTOs but not being tracked.

³⁷ United Nations Environment Programme. (2023, September 12). *Building materials and the climate: Constructing a new future*. <https://www.unep.org/resources/report/building-materials-and-climate-constructing-new-future>



	Life Cycle Cost (LCC) assessment	Qualitative index	Indicates whether Life Cycle Cost (LCC) assessment systems or other systems for tracking circularity are implemented in the infrastructure project.	Verify the presence of LCC assessment systems or other circularity tracking systems through project documentation, procurement records, and system implementation reports.		They are crucial for evaluating the total cost of ownership, including initial construction, operation, maintenance, and end-of-life disposal - which can help in furthering circularity in the system.	Within scope of PTOs, but difficult to implement or track. LCA is a complex process that requires specialised knowledge and skillsets.
	Circular Economy Competency Development	%	Capacity building initiatives such as workshops, online courses/webinars, industry collabs etc. for employees that can improve knowledge and awareness on circular economy.	Measure of the total number of CE focussed initiatives out of the total number of capacity building exercises carried out for employees in a fixed time period.	Information on training calendars, HR plans and strategies, Certification or partnerships with CE education providers, post-training assessments or feedback reports.	Competency development fosters organizational readiness, reduces resistance to change, and enhances innovation by embedding CE thinking across roles and departments.	Within the scope of PTOs, and the indicator is trackable.
Extend	Retrofitting and repair	% or scoring index	Proportion of maintenance activities that successfully.	Track the number of successful maintenance interventions divided by	Asset management plans and	Extending the life of infrastructure	Within the scope of PTOs and the indicator is

			extend the lifespan of infrastructure components.	the total maintenance activities for predetermined unit of time OR Assessing financial investment in repair vs new procurement.	maintenance schedules, Records of repair, retrofitting, or refurbishment projects, Inventory of rolling stock and infrastructure upgrades, Interviews with maintenance and operations personnel.	through targeted upgrades supports environmental sustainability, cost savings, and service continuity management.	already being tracked by several PTOs.
	Operational Emission Intensity	tonnes CO2e/passenger-km	Estimate of the greenhouse gas emissions per passenger-kilometre during operation.	Total GHG emissions generated, divided by the total passenger-kilometres of the vehicle. Operation done for defined reporting period.	Fuel consumption records, Emission factor values, Vehicle-kilometres or passenger-kilometres operated, fleet characteristics.	Helps in assessing the environmental impact and promoting low-emission technologies.	Within the scope of PTOs and the indicator is already being tracked by several PTOs.
	Shared Infrastructure Use	%	Extent to which physical infrastructure (e.g., stations, depots) is shared between different modes or services to reduce redundancy.	Calculate the proportion of infrastructure that is shared, based on either physical dimension (e.g., floor area), number of facilities, or functional capacity. Data can be obtained from	Infrastructure asset inventories, facility usage logs or schedules, inter-agency sharing agreements,	This strategy reduces the need for duplicative construction and maximizes asset utilization, it contributes to lower material	Within the scope of PTOs and the indicator is already being tracked and implemented by several PTOs.

				infrastructure asset inventories, operational agreements, or facility management records.	interviews with infrastructure and operations managers.	consumption, reduced land use, and improved cost efficiency. It also facilitates intermodal connectivity and supports more seamless passenger experiences.	
Transform	Material recycling rate	%	Refers to the ability to reclaim, recover, or repurpose materials and components at the end of their useful life.	Recycling Rate - Calculation of the percentage of materials (by weight, volume etc.) that are recycled compared to the total amount generated or used. ³⁸	Inventory of recyclable materials and their properties, Historic data on performance and condition of assets containing recycled components throughout lifecycle, Waste management logs or reports, facility-level waste sorting and disposal records,	Implementation and tracking of this indicator helps reduce environmental footprints, lower disposal costs, and meet regulatory compliance on waste diversion.	Within the scope of PTOs, and the indicator is trackable.

³⁸ Stipanovic, I., Skaric Palic, S., Rodik, D., Indacoechea Vega, I., Pascual Muñoz, P., Martin-Portugues Montoliu, C., Bartolomé Muñoz, C., & Tomar, R. (2024). *Holistic circularity framework* (Deliverable D1.1). CIRCUIT Project. https://www.circuitproject.eu/wp-content/uploads/2024/06/circuit_d1.1-holistic-circularity-framework_v6_final_ipk.pdf



				CE4CE	Contracts or service agreements with recycling vendors.		
Material reuse rate	%	Refers to the ability of an object or component to be used multiple times for various purposes without losing their function and without significant degradation in quality or performance. In essence, it involves extending the lifespan and utility of a resource beyond its initial intended use.	The percentage (by weight, volume etc.) of total materials used are reused at the end-of-life cycle	Inventory of reusable materials and their properties, asset recovery and refurbishment records. Historic data on performance and condition of assets containing recycled components throughout lifecycle.	Material reuse sits higher on the waste hierarchy than recycling, as it preserves more of the embedded energy and labor in products. Fostering reuse reduces demand for virgin materials, lowers lifecycle costs, and extends the utility of assets.	Within the scope of PTOs, and the indicator is trackable.	
Proportion of wastage	%	Refers to the materials & wastes going to landfilling, incineration or lost at the end of life cycle or during life cycle of a system/structure/element.	The percentage of materials (by weight, volume etc.) that go to waste or completely lost at end-of-life cycle.	Quantity of materials used. properties of the materials, Waste disposal logs and contractor reports, Construction or maintenance logs indicating surplus	High wastage rates indicate inefficiencies in material use and highlight areas for improvement in resource management.	Within the scope of PTOs, and the indicator is trackable.	



				CE4CE	or rejected materials.		
Disassembly potential	Qualitative - Grades or scoring index	Level of capacity of a product/system/structure or built asset to be disassembled at the end of its useful life so that parts and components can be recycled, repurposed, or used in other ways to be diverted from the waste stream.	Assess the design and construction of infrastructure components based on criteria such as modularity, use of reversible connections, and the presence of disassembly instructions. Assign a score to each criterion and calculate an overall index value.		Type of structure, inspection and monitoring data, information on fastening and structure joints, design and engineering specifications.	Enables effective recovery of parts and materials, reducing the need for virgin resource extraction and minimizing waste at end-of-life. Contributes to sustainable decommissioning practices and lowers the total environmental footprint of infrastructure and assets.	Within the scope of PTOs, and the indicator is trackable.

The indicators presented in this chapter offer a structured yet adaptable framework for assessing the implementation of circular economy principles in public transport infrastructure. The indicators are also rated as per the current scope of implementation by PTOs or future potential to do the same. Within the circularity framework of Avoid-Extend-Transform-Enable, the indicators try to capture a wide range of lifecycle stages—from construction and operational phase to end-of-life recovery stage. These indicators provide practical entry points for public transport authorities and other stakeholders to monitor, evaluate, and enhance circularity within their systems. While not exhaustive, the set is designed to evolve alongside technological advancements, policy developments, and industry best practices. Ultimately, the use of such indicators can guide more informed decision-making, support regulatory compliance, and foster innovation in the transition toward a more sustainable and circular public transport ecosystem.

6. Conclusions and recommendations

This strategy examines public transport infrastructure (PTI) through the lens of the AETE circularity framework, offering a life cycle approach that can drive transformative change in infrastructure management. It promotes a more holistic way of planning, using, maintaining, and decommissioning assets to reduce resource use, boost resilience, and respond to environmental, social, and economic challenges.

The strategy serves as a flexible foundation for developing CE4CE Action Plans and beyond, aiming to support wider adoption of circularity principles among European public transport organizations. In addition to specific recommendations in each section, this document outlines overarching conclusions to support the creation of localized, actionable plan

Adopt a life cycle approach in planning, construction, and management

Public transport operators and asset managers are called upon to move beyond isolated, piecemeal actions and fully embrace a life cycle, systemic perspective when managing public transport infrastructure. While individual efforts are valuable, real impact comes from coordinated actions across the entire life cycle, aligned within a circularity framework guided by clear priorities and steps. To prioritize effectively, decisions should be data/evidence-driven, considering a wide range of impacts—not just costs, energy use, or CO₂ emissions—but all factors that contribute to significantly reducing natural resource consumption and ecological harm.

Even if not directly involved in every stage, public transport operators and asset managers play a vital role as enablers by leading within their scope and influencing progress through procurement, collaboration with stakeholders, and advocacy where direct their action is limited.

Consolidate existing improvements in the operational stage of PTI

There are promising initiatives underway to extend the lifecycle of assets while maintaining strong performance. Public transport operators and other direct asset managers are encouraged to continue and accelerate this good work. Ongoing initiatives include, but are not limited to, embracing technology benefits such as smart building systems and predictive maintenance for railways—moving toward more automated detection and expanding these systems across all assets. Other key actions involve finding commercial alternatives or agreements for critical spare parts, including remanufacturing worn components, sourcing from second-hand markets, or using innovative technologies like 3D printing to produce parts no longer available on the



market. Additionally, there is growing ambition to increase the use of recycled materials, such as recycled concrete in buildings and recycled ballast and sleepers in railways.

Prioritize “Avoid” and “Transform” stages via circular procurement

Although circularity efforts in the operational phase are advancing, the “Avoid” and “Transform” stages still need greater attention. “Avoid” is especially critical as it has the highest ecological leverage and sets the course for later stages. “Transform” focuses on reducing waste and demand for scarce resources—key drivers of biodiversity loss.

Public transport authorities may not directly control these phases, but they wield powerful influence through procurement. When operators demand low carbon, recycled, or modular assets, industry responds. Circular procurement is a proven tool to reshape markets—especially when aligned with instruments like the EU Green Public Procurement Regulation and strengthened through early dialogue with industry. Setting clear requirements and shared goals from the start will accelerate adoption of circular practices in manufacturing, construction, and decommissioning.

Advocate for transformative policy measures to break linear models

Last but not least, real circularity cannot be achieved without ambitious policies that promote innovative approaches and create a level playing field, which are essential to overcoming the structural barriers maintaining the linear model. While some progress has been made through existing regulations, more work is needed. Current policy discussions that are moving in the right direction, revolve around including strengthening green public procurement with concrete incentives to prioritize assets with better life-cycle environmental performance over price, regulations that opt out waste by making recycling and recovery standard practices, and clear, harmonized guidelines for establishing an EU-wide second-hand market for transport parts and assets. These measures would help pave the way for national and local public authorities to implement and enforce policies tailored to their specific local contexts.

Foster cross-sector collaboration

Circularity in PTI cannot succeed without collaboration—across departments, organizations, and industries. For instance, the lifespan of rail and cableway systems is often compromised by the lack of spare parts, many of which are obsolete or difficult to repair. Public transport operators



must work together to consolidate needs and engage local manufacturers who can benefit from economies of scale and provide long-term solutions.

Likewise, buildings designed for disassembly and material recovery will only become standard if public transport infrastructure funders and managers actively demand it from the construction sector. This is not merely a technical issue—it's an institutional challenge that requires trust, commitment, and aligned intent among all stakeholders.